Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

The Relationship between Heat Flow Regime and Active Tectonics Inferred from Seismological Data in Western Anatolia

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Keywords: Geothermometers, Heat flow, Active tectonics, Seismology, Western Anatolia, Turkey

ABSTRACT

The hydro-chemical data sets of many hot springs in the Anatolia obtained from available reports of Mineral Research Institute (MTA) and literature are used to calculate terrestrial heat flow values around western Turkey. These data sets include surface temperature, conductivity, alkalinity, acidity, TDS, pH values, H_2S, Ca, Cl, F, Fe, K, Mg, Mn, Na, NH_3, SiO_2, SO_4 contents, their locations, usages and other relevant information. The silica heat flow interpretation technique is applied to available hot springs. For this purpose, quartz (silica) and Na-K-Ca geothermometer calculations were firstly made. The heat flow values then derived from silica geothermometer and were imaged on the seismological pattern over the western Anatolia. Several pictures showing qualitative relationships between heat flow regime and active tectonic inferred from seismological data were constructed for some focussed regions. Our interpretations indicate that heat regime in the western Anatolia is well associated with active tectonics.

1. INTRODUCTION

Turkey is located within an important geothermal area, and has an estimated 31,500 MWt geothermal heat potential (Mertoglu et al., 1995). The main utilization of geothermal energy in Turkey is in domestic heating, greenhouses, and in spas and thermal resorts installed for balneological purposes. Additionally, electricity is produced from geothermal energy in the first and only power plant installed in the Kizildere field West Anatolia ; the plant has been in operation since 1984 with a capacity of 20 Mwe.

On the other hand, Turkey is an excellent natural laboratory to study post-collisional intracontinental convergence- and tectonic escape-related deformation, and the consequent structures that include fold and thrust belts, suture zones, active strike-slip faulting, and active normal faulting and the associated basin formation (Figure 1; Bozkurt, 2001).

Turkey forms one of the most actively deforming regions in the world. Turkey is one of the most seismically active regions in the world (Figure 1). As a result, it has a long history of large earthquakes including the Kocaeli (M = 7.4) and Düzce (M = 7.2) events of 17 August and 12 November 1999, near Istanbul. It is located within the 'Mediterranean Earthquake Belt', whose complex deformation results from the continental collision between the African and Eurasian plates.

Unlike western Anatolia, a large number of heat flow measurements are available in Europe and the surrounding seas. The Biga peninsula, Gediz graben (between Manisa and Salihli), B. Menderes graben (between Germencik and Denizli), Dikili, Izmir, Bursa and Eskisehir that are well known as geothermal sites are located in western Anatolia.

The chemical compositions of a total of 247 thermal water samples from 30 city in Western Anatolia are composed from Turkish Mineral Research and Exploration (MTA) reports and early articles. In this study, we calculated reservoir temperatures of the geothermal systems in western Anatolia using SiO_2 and Na-K-Ca geothermometers. Both temperature values and heat flow values derived from these temperatures are then imaged with seismological pattern of the western Anatolia.

2. GEOLOGY, SEISMOLOGICAL DATA AND THERMAL REGIME

Temperature distribution within the earth's crust has important effects on the active tectonics and seismicity (Bott, 1982). Even though it is one of the most important parameters in the earth, our knowledge of the thermal state within the crust is poor. Temperature measurements are usually restricted at shallow depths and are under the influence of fluid motions, topography and local geology (Beardsmore and Cull, 2001).

The major neotectonic structures shaping Turkey and adjacent areas are the right-lateral North Anatolian Fault System (Figure 1) (Bozkurt, 2001). Many host and graben systems are located within the Western Anatolia. These systems have several hot springs with various temperatures (Figure 2; Ilkisik, 1995). The distribution of hot springs in Turkey roughly parallels the distribution of the fault systems and the Tertiary–Quaternary volcanics (Mutlu and Gülec, 1998)

The present geomorphology is characterized by a series of east-west trending major grabens with northeast-southwest trending secondary (crosscutting) grabens (Koçyigit, and Özacar, 2003). Western Anatolia is one of the most rapidly deformed continental regions in the earth, and the present widely spread seismicity is an indicator of this deformation. However, there is a close association between the present day deformation and the rate of convergence and subduction along the Hellenic –Cyprus Arc.

2. 1. Seismotectonics of the Western Anatolia

The western Anatolia is seismically active associated with many major and moderate graben systems as presented by earthquake data (Taymaz et al., 1990; Taymaz and Price, 1992). Active tectonics of the Western Anatolia is evolved as a result of the interaction between the African, Arabian and Eurasian plates.

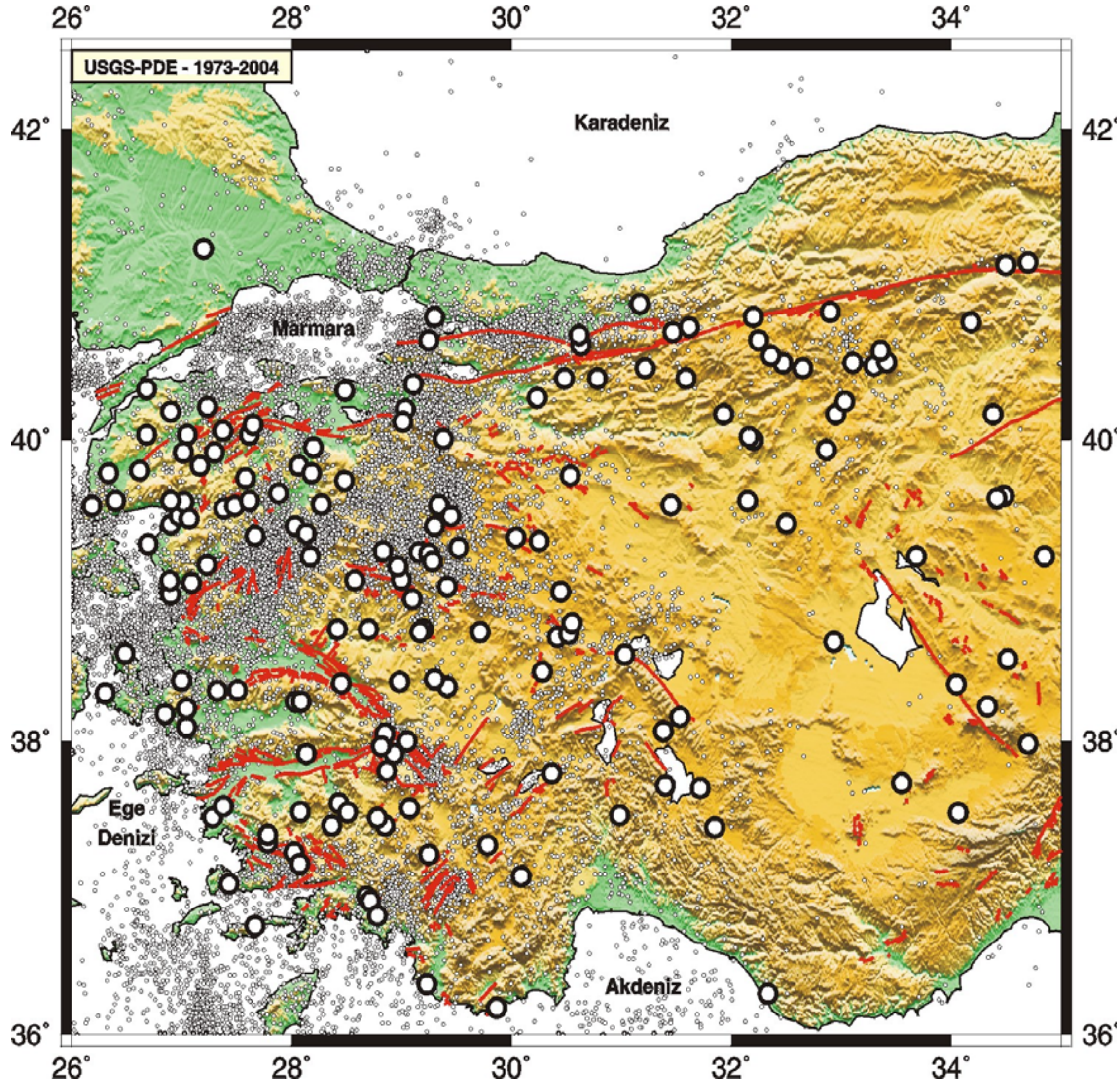

Figure 1: Distribution of epicenters of earthquakes with M≥2 that occurred between 1900 and 2001 in western Turkey (gray small dots). Hot springs (circles) and major faults (red lines) based, in part, on earthquake data.

Due to the subduction of the eastern Mediterranean lithosphere under the Aegean along the Hellenic Arc (Papazachos and Comninakis, 1971; LePichon and Angelier, 1979), counterclockwise rotation (LePichon et al., 1995; Cocard et al., 1999; Kahle et al., 2000; McClusky et al., 2000) and westward motion of Anatolia (McKenzie, 1970, 1972; Taymaz et al., 1991), intense seismic activity and high strain rates have been observed in this region. Arabia/Eurasia collision progressing in eastern Turkey caused Anatolia to move to the west and the North Anatolian Fault to propagate into the Aegean, where the early slow extension started to be modified about 5 Ma ago (Armijo et al., 1996). Western Turkey and the north Aegean Sea have thinner crust and lower elevation than the Anatolian plateau of central Turkey (Makris and Stobbe, 1984).

During Early Miocene times, Aegean-Anatolian plate reveals that north-south trending graben basins which are the most prominent structural and morphological features and they were formed under an east-west extensional regime (Yılmaz, 2002). Groups of grabens**,** E-W-trending Gediz graben and its neighboring NE-SW-trending Gordes, Demirci, and Selendi grabens form an important graben system and they account for most of the seismic events of Western Anatolia. It is further widely accepted that large active normal faults accommodate the observed rapid extension and control the geomorphology.

The NE-SW trending Burdur, Acıgöl and Baklan, and NW-SE trending Dinar and Sultandağ - Akşehir basins all bounded by large faults form a system of half-graben whose orientation is evident in both the topography and the tilting of Neogene sediments adjacent to them (Taymaz and Price, 1992; Taymaz, 1993; Taymaz et al., 2002).

3. GEOTHERMOMETER CALCULATIONS

This study links hydrogeochemical data with heat flow, following the silica heat flow interpretation technique of Swanberg and Morgan (1979, 1980). The technique applies silica geothermometry (the quartz geothermometer) to non-thermal groundwaters. The quartz geothermometer works by recording and preserving the temperature at which thermodynamic equilibrium was last reached between groundwater and quartz. This allows an estimation of subsurface temperature. For this purpose following equation is used.

$$T_{SiO_2} = \frac{1315}{5.205 - \log_{10}[SiO_2]} - 273.15 \quad (1)$$

where $TSiO_2$ is the silica geotemperature in ^0C and $[SiO_2]$ is the concentration of dissolved silica expressed in ppm. By determining $[SiO_2]$ (obtained by chemical analysis of the groundwater), the temperature at which silica last equilibrated with groundwater can be estimated if the dominant silica polymorph could be determined. The equations for the calculations of geothermometer can be summarized in Table 1.

The silica geotemperature of the groundwaters was obtained by substituting the dissolved silica content of a groundwater into the quartz geothermometer equation (Truesdell, 1976).

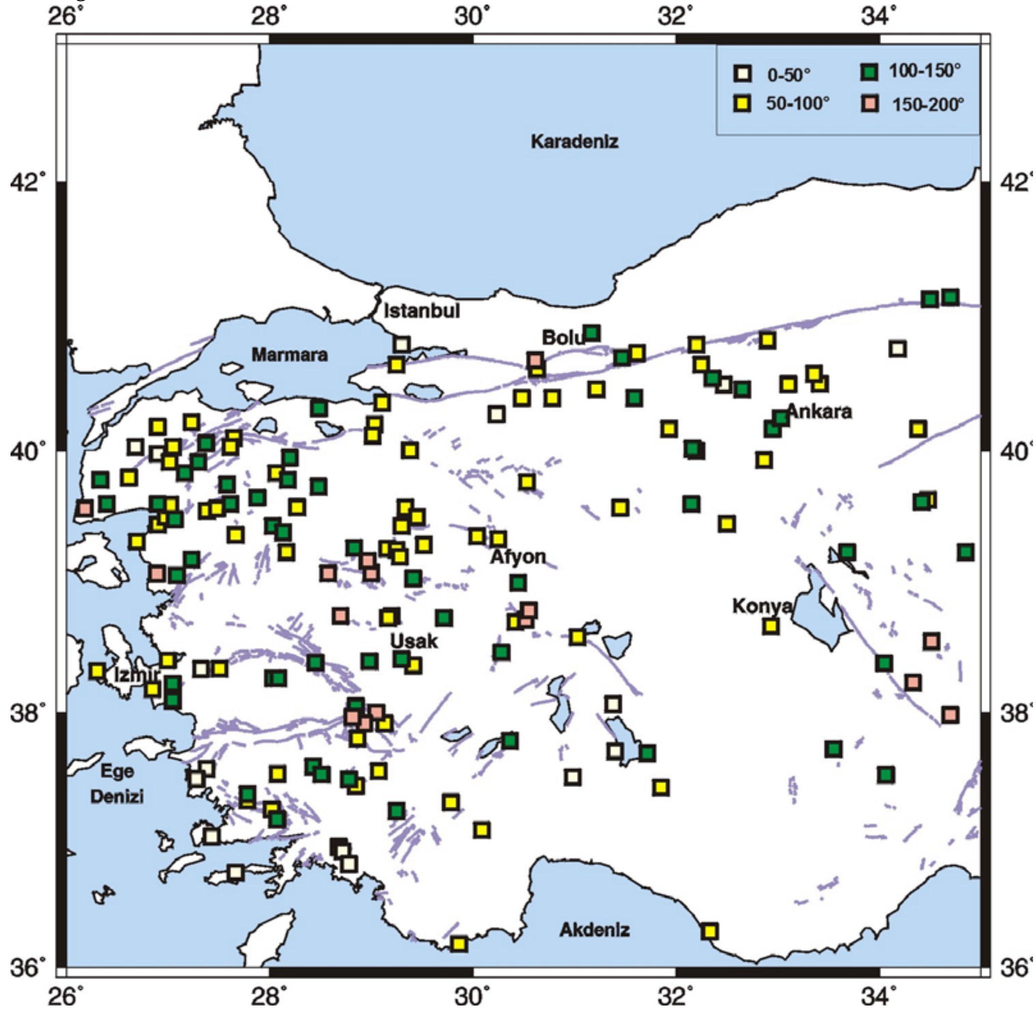

Figure 2: Temperature distribution calculated from silica geothermometer using Equation 1.

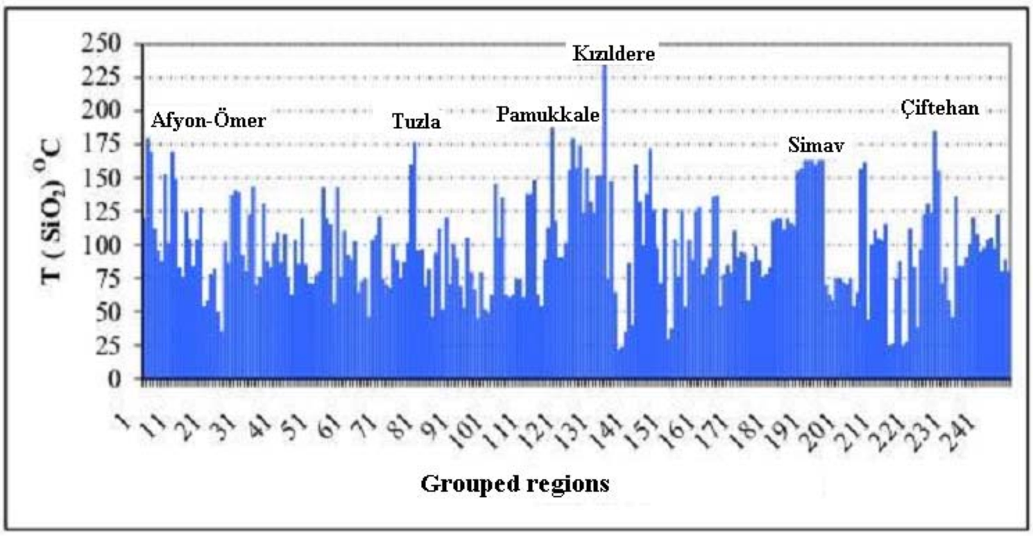

Figure 3: The calculated Silica temperatures for grouped geothermal regions using SiO_2 geothermometer

Table 1: Geothermometers and related calculations

Geo-thermometers	Equation	Limitations
Na/K (Fournier, 1982)	$T=[1217/(\log_{10}(Na/K)+1.483)]-273.15$ ºC	T>150 ºC
Na/K (Truesdell, 1976)	$T=[855.6/(\log_{10}(Na/K)+0.8573)]-273.15$ ºC	T>150 ºC
Na-K-Ca	$T=[1647,3/(2,24+\log_{10}(M_{Na}/M_{K})+\beta\log_{10}(\sqrt{M_{Ca}}/M_{Na}))]-273.15$ ºC	β=4/3, T<100 ºC β=1/3, T>100 ºC
Na/Li	$\log_{10}(Na/Li)=1000/T-0.39$ $\log_{10}(Na/Li)=1000/T+0.13$	Cl<0.3 m Cl>0.3 m

Note: M_X = Molar consantratation of the element X.

Water samples used in the present study were collected in different years by a number of workers. Most of the collected samples were analyzed at the MTA laboratories. For our calculations, hydro-chemical data of the hot springs (Didik and Tekin, 1996; Isik and Dilemre, 1995, 1996, 2000; Mutlu and Gülec, 1998; Oktu et al., 1991; Oktu, 1993; Oktu and Dilemre, 1997; Uzel and Dilemre, 1995) were used. $TSiO_2$ (^{0}C) temperatures are calculated for the Western Anatolia using Silica geothermometer and shown in Figure 2. Figure 3 also shows these values as the histogram versus grouped geothermal regions. Main geothermal sites are given within the figure.

The silica heat flow interpretation technique also makes a major assumption that all groundwaters have a similar minimum mean circulation depth and that the thermal conductivity of the Earth is the same to that depth, an assumption that is not rigorous in many local areas, but may not be unreasonable with a continental-scale database (Swanberg and Morgan, 1980).

$T_{Na-Ca-K}$ geothermometer calculations are made using all data from hot springs. The several hot springs sites are grouped as only one geothermal region. Calculated temperatures are then represented as the histogram picture to give a gualitative interpretation (Figure 4).

The heat flow calculations were made using an approach indicated by Ilkisik (1995). Calculated heat flow values are grouped in terms of known geothermal sites in western Anatolia (Figure 5). Additionally, all grouped values are then imaged to the seismological map to obtain an idea about the relationship between heat flow and active tectonic.

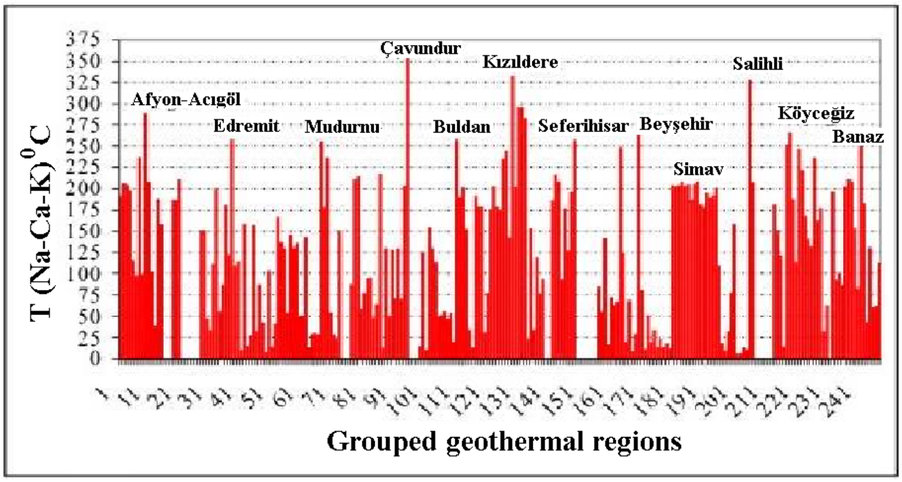

Figure 4: The calculated temperatures for grouped regions using Na-K-Ca geothermometer.

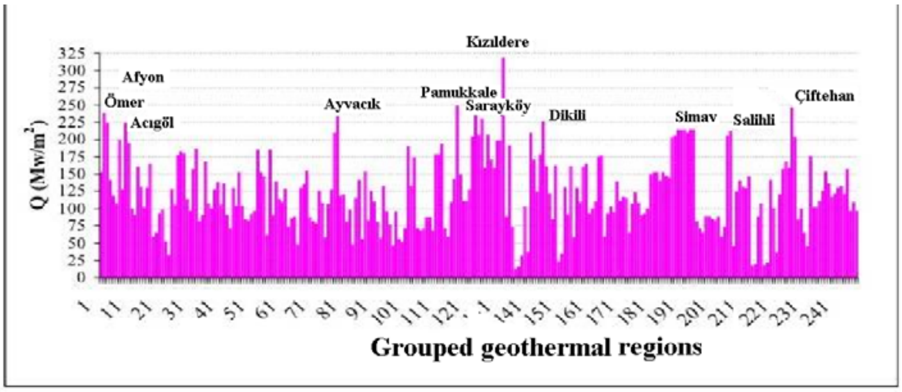

Figure 5: Heat flow values approached using silica temperatures.

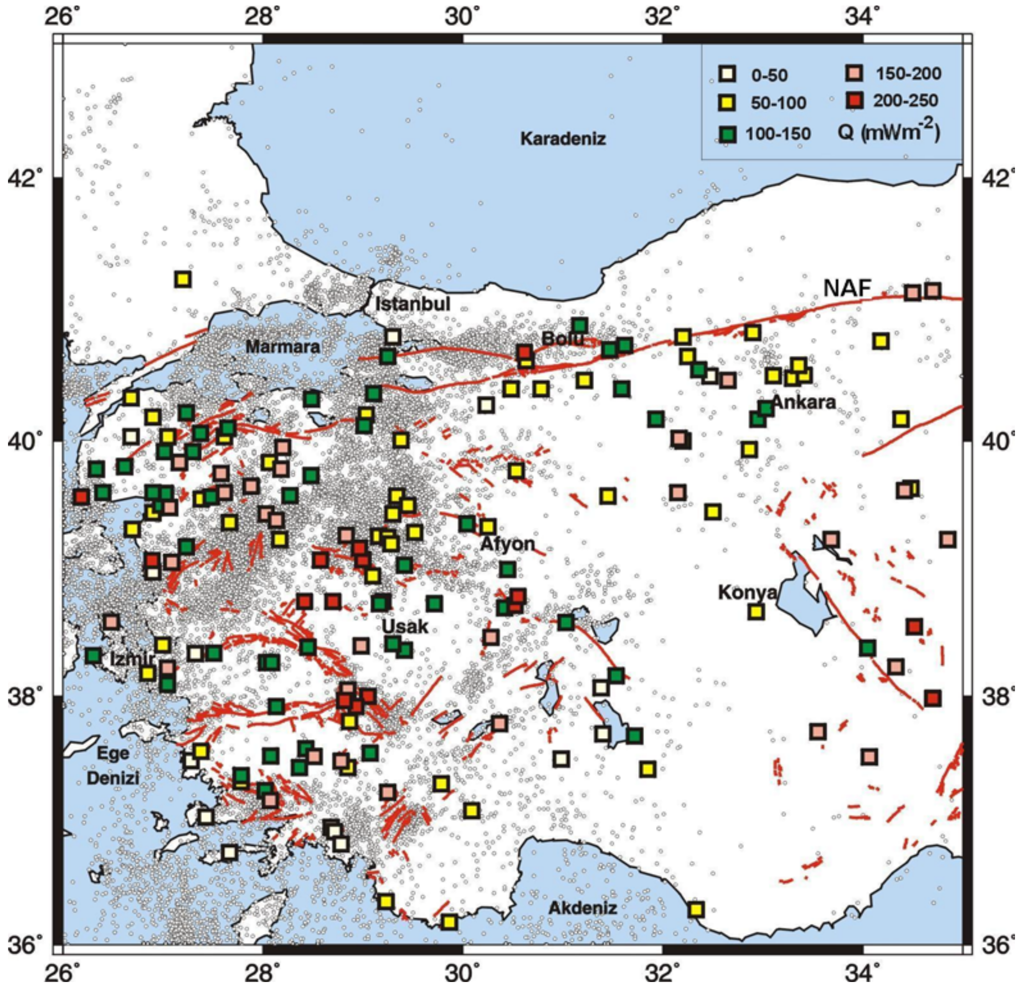

Figure 6: Distribution of calculated heat flows and seismological pattern of the western Anatolia.

The important geothermal areas of North Anatolia are located along one of the major neotectonic structures seismically active zones of Turkey, namely the North Anatolian Fault (NAF). West Anatolian extensional province is characterized by a series of grabens, widespread volcanics of Neogene age Quaternary volcanism being restricted only to a small area around Kula, crustal thinning and high heat flow values above the world average (Cermac and Hurtig,1979; Tezcan, 1979).

4. DISCUSSIONS AND CONCLUSIONS

The first heat flow map for Turkey was published by Tezcan (1979) using the measurements in the wells drilled for geothermal energy. This map has been revised by including temperatures measured in 204 oil and coal wells mostly drilled in the south-eastern Turkey and Thrace (Tezcan, 1995). He calculated heat flow using geothermal gradients in exploration wells and assuming a constant thermal conductivity because no thermal conductivity measurements were performed in the wells.

In present study, the silica heat flow interpretation technique has been applied and tested in mainland Turkey, using a database of approximately 247 Turkey groundwater analyses. The silica geotemperature of the groundwaters was obtained by substituting the dissolved silica content of a groundwater into the quartz (silica) geothermometer equation (Truesdell, 1976). By using all chemical composition dataset the temperature (TºC) calculations were made and from the silica temperature and then the heat flow (Q mW/m^2) values were estimated with the chemical geothermometer correlations (Ilkisik, 1995).

Na-K-Ca and SiO_2 (silica). Geothermometer applications resulted mean temperatures are; SiO_2 (silica) 125ºC -150 ºC, Na-K-Ca 150ºC -200 ºC and mean heat flow is 100 mW/m^2 - 150 mW/m^2. The highest estimated values and locations are; SiO_2 (silica) temperature at Denizli- Kızıldere

235ºC, Na-K-Ca temperature at Çankırı- Çavundur 355 ºC and heat flow value at Denizli-Kızıldere 318 mW/m^2. The results reveal that the heat flow values are high in this region. Also, estimated values placed on map of could be associated with West Anatolia's seismic and tectonic features. The northwest Anatolia generally has high values. In the northern Aegean, temperatures are highest for upper and lower crust. It can be associated with active tectonics and high geothermal activity (Mutlu and Gulec, 1998).

High heat flow and seismicity, intensive faulting and volcanism are the main characteristics of the region. Tezcan (1995) mentions that the heat flow values over Anatolia are much higher than those over the Meditterranean Sea and Black Sea. A similar result was also reported by Ilkisik (1995). He calculated a mean heat flow value as 107±45 mWm-2, which is approximately 50% higher than the world average. Also, the surface temperatures of hot springs in the western Anatolia are generally higher than those in the eastern Anatolia. Moreover, there is substantial thermal activity in the area revealed by numerous hot springs, fumaroles, hydrothermal alterations and recent mineralizations as inferred by deep electrical structure (Caglar and Isseven, 2004). Major geothermal fields are usually associated with the horst-graben systems and active-subactive volcanism. For instance, the Kizildere and Pamukkale geothermal fields exist in the Büyük Menderes graben. Especially, major geothermal systems exist where the northsouth and east-west trending horst-graben systems intersect each other.

According to our calculations (Figure 6), the eastern Mediterranean Sea has relatively low heat flow values mainly in the southern part. Also, low heat flow is observed in the Black Sea. In the Aegean Sea several high heat flow value regions connected with tectonic zones are observed. The highest heat flow (>120 mWm-2) in northwest Aegean may be related to the subduction zone.

The overall heat flow values over western Anatolia are generally much higher than those over the Mediterranean Sea and Black Sea, although a poor heat flow measurement coverage is available in Turkey (Tezcan, 1995). From our interpretations, high heat flow anomalies connected with tectonic zones are observed (Figure 6).

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