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High heat generating granites of Kestanbol: future enhanced geothermal system (EGS) province in western Anatolia

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Abstract: Although the western Anatolian region is a foci for hydrothermal systems, this region has several high heat-generating granitic intrusive bodies that qualify to be candidates for enhanced geothermal systems (EGS). Considering the future energy requirement, carbon dioxide emissions reduction strategies, food, and water security issues, these granites appear to be the future clean energy source for the country. One such granite intrusive is located in the Kestanbol area in the western Anatolian region. The radioactive heat generation of this 28 Ma old granite varies from 5.25 to 10.38 μW/m^3 with a heat flow of 92.47 to 128.61 mW/m^2. These values concur with the measured geothermal gradients and heat flow values measured from exploratory bore wells. High radon content in the thermal waters in these areas indicates interaction between the circulating fluids and the Kestanbol granite. This is for the first time evaluation of the EGS potential of granite intrusive in Turkey has been made. The Kestanbol intrusive is placed under a compressive stress regime within the Anatolian-Aegean regional tectonic framework.

Key words: Geothermal energy, EGS, radionuclide, granite, Turkey

1. Introduction

Within the Alpine-Himalayan orogenic regime (Tethys regime), the Anatolian fault zone and associated tectonic structures and geothermal provinces occupy an important segment. The Paleotethyan and Neotethyan ocean basins outcrop between the E-W trending tectonic belts, namely, the Pontides, Anatolides, and Taurides. The E-W trending Neotethyan Subduction zones hosts, besides obducted Cretaceous ophiolites, several granitoid intrusives (Bingol et al., 1982; Örgün et al., 2007; Dilek et al., 2009; Şahin et al., 2010; Black, 2012; Angı et al., 2016). These granitoids outcrop at several places in the western, central, northeast, southeast Anatolia. The granitoids in west Anatolia is of Eocene-Oligo-Miocene in age, while the rest belong to the Late Cretaceous age. These granitoids show high natural radioactivity levels due to high concentrations of uranium, thorium, and potassium. As a result, these rocks generate abnormal heat greater than the heat generated by normal granites discussed in the later sections. The heat can be extracted through circulating fluids, and the heat can be utilized for power generation and other direct applications. In this paper, our focus is on the Kestanbol granitoids of the Biga Peninsula in western Anatolia. This 28 Ma granitoid is intruded into the Rhodope-Serbo-Macedonian Massif and outcrops over an area of 16 sq. km. The Upper Miocene-Pliocene coarse-grained clastic and shallow marine carbonates overly intrusive. The concentration of uranium, thorium, and potassium in these granites is the highest of all the granites of Turkey. The distribution of granites in Anatolia is shown in Figure 1.

2. Geology of western Anatolia

During the Cenozoic Era, western Anatolia experienced intensive magmatic activity represented by volcanic and plutonic rocks (Figure 2). Several authors have reported the geology, geochemistry and tectonic configuration of these rocks (Şengör and Yılmaz, 1981; Yılmaz, 1989; Güleç, 1991; Harris et al., 1994; Altunkaynak and Yılmaz, 1998; Aldanmaz et al., 2000; Okay and Satır, 2000, 2006; Köprübaşı and Aldanmaz, 2004; Altunkaynak and Dilek, 2006, 2013; Dilek and Altunkaynak, 2007, 2010; Altunkaynak and Genç, 2008; Boztuğ et al., 2009; Ersoy et al., 2009; Erkül, 2010, 2012; Hasözbek et al., 2010; Altunkaynak et al., 2010, 2012a, 2012b; Erkül and Erkül, 2012; Erkül et al., 2013; Papadopoulos et al., 2016). The plutonic rocks are represented by I type granitoids and medium to high potassium calc-alkaline rocks (Harris et al., 1994; Köprübaşı and Aldanmaz, 2004; Altunkaynak, 2007; Altunkaynak et al., 2012a). All the granitic intrusive occur along fault zones (Figure 2). The older Eocene

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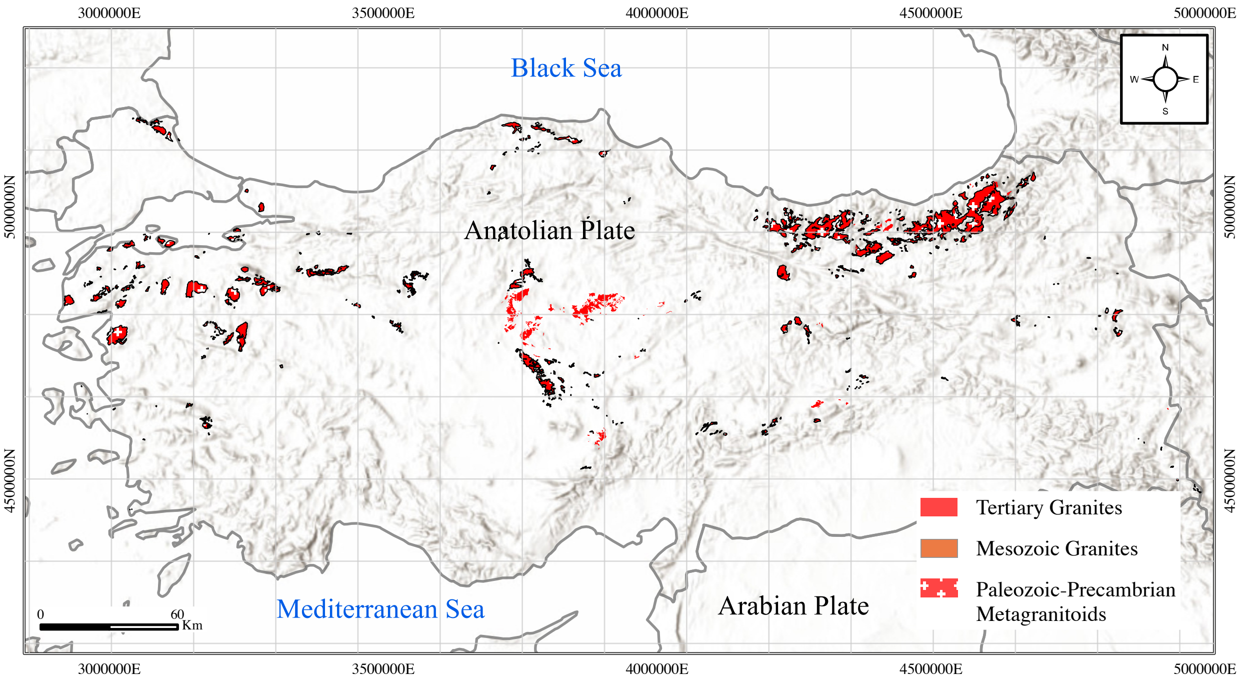

Figure 1. Occurrence of granites in Turkey (modified after Akbaş et al., 2011).

granite plutons outcrop along the İzmir-Ankara Suture (IAS) zone. Greater than 12 granite and granitic plutons outcrop in the western Anatolia zone (Figure 2).

The Eocene granitoids include granite, quartz diorite, granodiorite, syenite, and monzogranite. They are intruded into the Cretaceous blue-schist and ophiolites. The quartz diorite, granodiorite, and syenite occur around Orhaneli, Topuk, and Gurgenyala. In contrast, monzogranite, granodiorite, and granite occur around Yalova, Fıstıklı (Armutlu), Karabiga, and Kapıdağ, south of Marmara Sea and north area (IAS). The quartz diorite, granodiorite, and syenite are intruded into the Cretaceous blueschists and ophiolites. At the same time, the 35 million-year-old monzogranite and granite are emplaced into the metamorphic rocks of western Pontides (Delaloye and Bingöl, 2000; Altunkaynak et al., 2012 a,b). The older Miocene granitoids (younger) exposed towards the west of Anatolia contain higher radioactive elements such as U, Th and K compared to those granitoids of Eocene age. Thus, the heat-generating capacity of these granites is higher relatives to the Eocene (older) granites. This paper focuses on the Miocene granites of western Anatolia, particularly those occurring in the Kestanbol Region.

3. Geothermal gradient and heat flow over western Anatolia

The Aegean Sea, adjacent to western Anatolia, are loci of intense tectonic activity. This region is subjected to intense crustal extension and subduction accompanied by intense andesitic volcanism during the Oligocene (Fytikas et al., 1984; Dilek et al., 2009; Jolivet et al., 2015). These tectonic and volcanic activities have resulted in two major crustal extension regimes: an early E-W extension during Miocene to Early Pliocene and N-S extension during Pliocene to Quaternary. The younger extensional regime resulted in the formation of horst-graben structures in the Menderes Massif (Kocyigit et al., 1999). In addition, these active tectonic regime has resulted in high heat flow and high geothermal gradient in this region (Erickson et al., 1976; Eckstein, 1978).

Several deep exploratory geothermal gradient wells in and around the Tuzla geothermal field located south of Çanakkale in the western Anatolian region registered very high geothermal gradients and high heat flow values (Figure 3). The temperature of 145 °C was recorded at 50 m depth, and well-blow outs occurred due to high steam and boiling environment at such depths. Deep exploratory wells drilled to 800–1020 m into the pyroclastics recorded bottom hole temperatures of 173 °C (Karamanderesi and Ongur, 1974; Baba et al., 2005).

High-resolution equilibrium temperatures from 113 boreholes with a depth of 100 m were analyzed to determine the conductive heat flow in the western Anatolian region (Erkan, 2015). The coastal region extending from İzmir to Çanakkale showed elevated heat flow values varying from 85 to 95 mWm^2, while the region over the Menderes Massif recorded values above 100 mWm^2. The high heat flow values are associated with deep-seated normal or

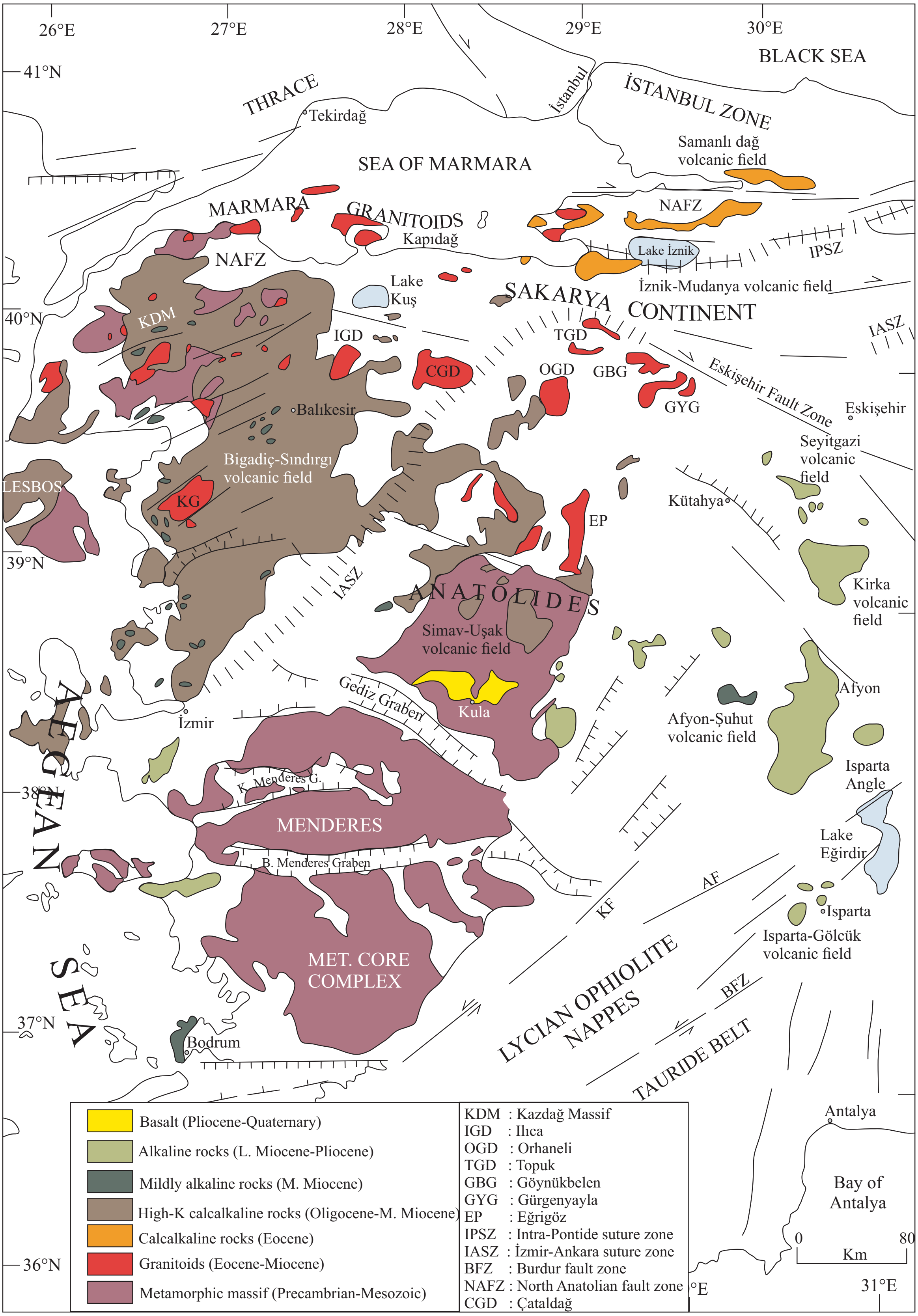

Figure 2. Simplified geological map of western Anatolia and the eastern Aegean region (modified after Dilek and Altunkaynak, 2009).

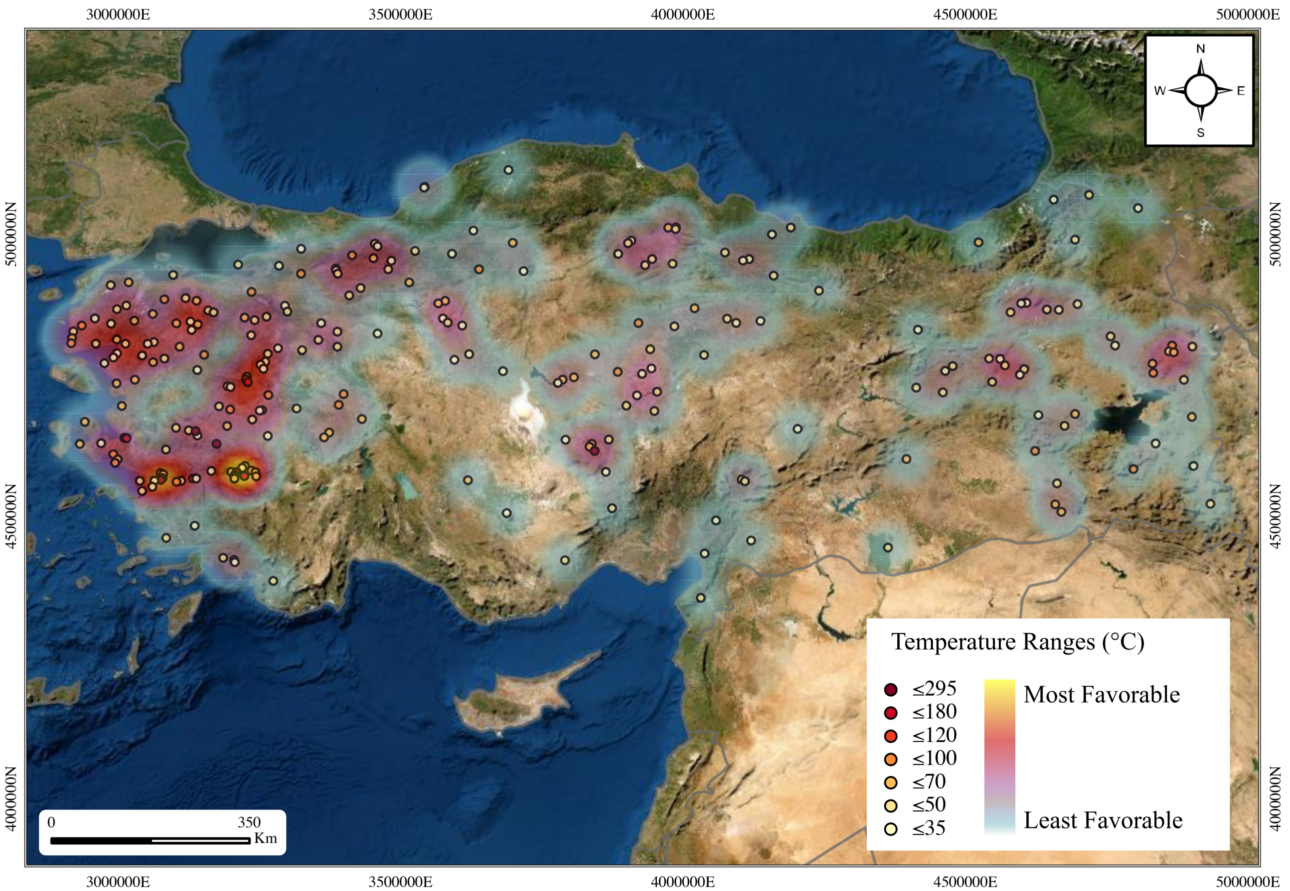

Figure 3. Geothermal sources of Turkey and their surface temperatures with favorability analysis (geothermal source data taken from Akkus et al., 2005; Basemap Imagery from Earthstar Geographics, Esri, HERE, Garmin, FAO, NOAA, USGS).

strike-slip faults and volcanic centers. These values are typical of regions related to orogenic (Mesozoic-Cenozoic) and volcanic activity (Cenozoic). In addition to borehole data, aeromagnetic data was also utilized to understand the subsurface structures responsible for high heat flow values (Eckstein, 1978). The Curie point temperature is essential to substantiate the anomalous heat flow in western Anatolia. The Curie point temperature (CPT) deduced from aeromagnetic was published for the western Anatolian region (Karat and Aydin, 2004). The high heat flow values lie over the regions where CPT is shallow.

In addition to the borehole exploration, airborne magnetic data was also employed to estimate the geothermal gradient and heat flow values using Curie point depth (Akin et al., 2014). The Curie point of depth (CPD), obtained airborne magnetic maps, was utilized to estimate the geothermal gradient. Heat flow values were obtained from the conductivity values and geothermal gradient. The heat flow value obtained varies from 100 to 160 mW/m^2 along the coastal region, extending from İzmir to Çanakkale (Akin et al., 2014). The Curie point of depth in these sites is also shallow varying from 10 to 6 km. The sites that recorded high heat flow values and shallow CPD include Balıkesir, İzmir, Manisa, Aydın, Denizli, and Çanakkale.

Although conventional heat flow measurements along western Anatolia are limited, heat flow measurements based on bottom hole temperatures established reasonable heat flow maps for the entire region (Tezcan and Turgay, 1991). The same data have been utilized to establish the geothermal gradient in this region.

The heat flow values vary from 50 to 133 mW/m^2, and the corresponding geothermal gradient varies from 39 to 57 °C/km; the higher values are recorded along the Agean Sea coast of İzmir and Çanakkale, i.e. Çanakkale and the peninsular part of İzmir. The Curie point depth calculated based on the aeromagnetic anomaly map along western Anatolia varies from 12 km (near İzmir) to 19 km over Çanakkale. In addition to the active tectonic regime of the Çanakkale region, resulting in high heat flow values, the presence of fertile granites in this region (granite with high content of uranium, thorium, and potassium) is making this region most suitable for initiating projects related to EGS (enhanced geothermal systems).

4. Geothermal provinces of western Anatolia

Due to high heat flow and geothermal gradients associated with active and intense tectonic and volcanic activities, this region has developed high enthalpy geothermal systems (with recorded reservoir temperatures approximately 240 °C) along the western Anatolia, represented by numerous thermal springs, with fluids circulating along the deep faults associated with the horst and graben structures (Serpen et al., 2009; Ugur et al., 2014). The surface manifestations of the geothermal systems are represented by thermal springs (Figure 4) with temperatures varying from 34 to 80 °C.

Exploratory bore-wells drilled near Tuzla (south of Kestanbol) indicate high-temperature geothermal systems in this province with a recorded bottom hole temperature of 145 °C from a 50 m deep bore well (Baba et al., 2005). Similarly, two exploratory bore wells drilled to a depth of about 1000 m reveal high-temperature systems at 333 m depth with a recorded temperature of 175 °C. Well blow-outs in this region indicate the presence of high-pressure geothermal systems. The geothermal systems are of two-phase with 13% steam and a fluid flow rate of 130 t/h (Baba et al., 2005). The presence of high-temperature hydrothermal alteration assemblages indicate reservoir temperature located in the pyroclastics of the order of 220 °C (Sener and Gevrek, 2000; Baba et al., 2005).

The Kestanbol thermal springs (47–68 °C) are historically famous for their healing properties. There are two groups of thermal springs, one with high sulfur content and the other with high radon content due to high radioactivity (Demirsoy et al., 2018). The presence of radionuclides has been established, and the source of the radionuclides is the high radiogenic Kestanbol granites (Baba et al., 2008).

A detailed account of the geothermal manifestation of Kestanbol was given by Baba and Ertekin (2007). The issuing temperature of the thermal springs varies from 66 to 76 °C with a flow rate of 6 L/s. Located near the seashore, the thermal water show mixing of seawater represented by high Na-Cl content. In addition, tritium content varies from 0.22 to 0.25 TU indicating deep circulation of the thermal fluids (Baba and Ertekin, 2007).

5. The Kestanbol granites

Western Anatolia experienced extensive magmatic activity during Eocene to Miocene period, represented by plutonic and volcanic activities (Yilmaz, 1997; 1998; Delaloye and Bingol, 2000; Yilmaz et al., 2001; Arik and Aydin, 2011). During this period, this region was under lithospheric spreading and crustal thinning (Aldanmaz, 2006). The earlier magmatic activity was represented by granitic pluton, and basaltic lava flows represented the late phase.

Kestanbol, located in northwestern Turkey, hosts young granitic and volcanic rocks. The younger granites were intruded into the metamorphic basement giving rise to a contact metamorphic aureole (Figure 5). The Kestanbol granitoid intruded into the metasedimentary rocks is a quartz monzonite related to the collision tectonic between Anatolian-Tauride and Pontides that occurred during the Late Cretaceous period. This N-S convergence continued until the Neogene period giving rise to magmatic activity in the Early Miocene (Karacik and Yilmaz, 1998; Sahin et al., 2010). The magmatic activity was represented by both intrusive and extrusive phases.

The volcanic rocks associated with the Kestanbol granites include lava flows, ignimbrites, and lahar deposits. The radiometric age ($^{40}Ar/^{39}Ar$) of the Kestanbol granites varies from 22.21 to 21.22 Ma (Early Miocene) (Akal, 2013). The Kestanbol granites are characterized by high uranium, thorium, and potassium content compared to other younger Eocene and Miocene granites of western Anatolia (e.g., Kozak pluton, Eybek pluton, Eğrigöz pluton, Koyunoba pluton, Karaburun granodiorite).

The Kestanbol quartz monzonite, emplaced into the regionally metamorphosed basement rocks, encloses several enclaves and is traversed by several dykes of aplite, pegmatite, mafic lamprophyre, and latite. The granitoid mass is widely exposed around the Kocali and Alada villages of Kestanbol (Arik and Aydin, 2011). The Kestanbol pluton was derived from crustal melts contaminated with mantle-derived mafic magma during its formation (Yilmaz et al., 2010). The Kestanbol quartz monzonites are holocrystalline with porphyritic texture with large potash feldspar megacrysts. Besides K-feldspars, these rocks contain plagioclase, quartz, biotite, hornblende and pyroxene in the groundmass (Arik and Aydin, 2011). The presence of thorite, uranothorite, allanite, and zircon either as inclusions in biotite and hornblende or as individual minerals, in considerable amounts, makes these rocks highly radiogenic (Örgün et al., 2007). Several dikes (approximately 2 m) of aplite, pegmatite, granophyre, and lamprophyre are found traversing the Kestanbol granitoid. These intrusive, together with hydrothermal alterations, created zones with a high concentration of radioactive minerals making these granitoids highly radiogenic (Orgun et al., 2007).

5.1. Radioactive characteristics of Kestanbol granites

The Kestanbol granitoid, due to the presence of significant content of radioactive minerals described above, is characterized by high radioactivity. Even the air around the area has registered very high gamma radiation levels varying from 46 to 9200 nGy/h (nanoGray/hour). Even the site near Kestanbol thermal springs reported a value of 880 nGy/h (Orgun et al., 2007). These values are considered very high for this region. The measured ^{137}Cs activities in the rock samples vary from 0.9 to 6.57 Bq/kg, which is regarded as very high. The concentration of U, Th, and K in the Kestanbol granitoid is shown in Table 1.

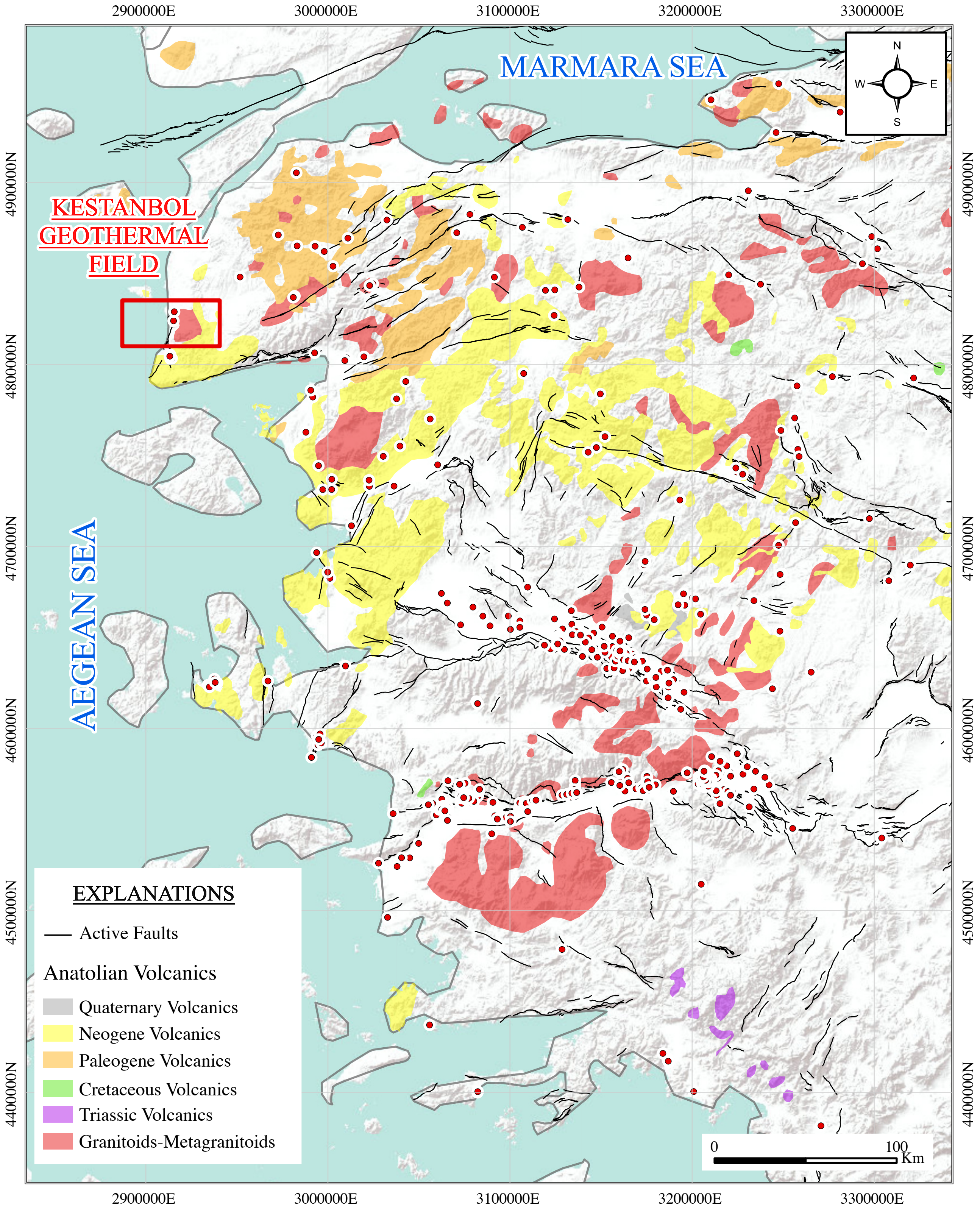

Figure 4. Geothermal provinces and thermal springs of Western Anatolia (modified after Akkus et al., 2005; Baba and Sozbilir, 2012; tectonic structures digitized from Emre et al., 2013).

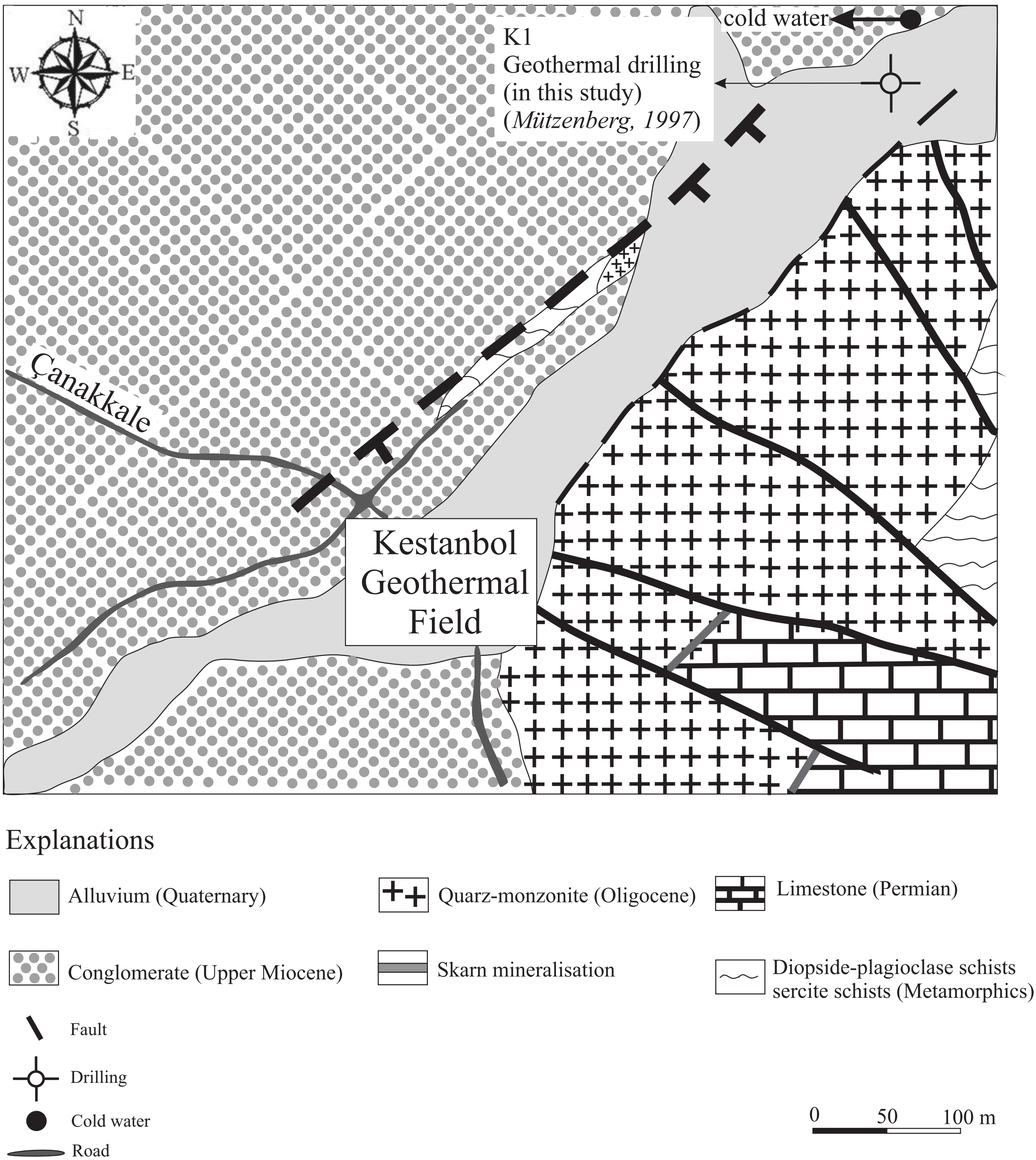

Figure 5. Granite exposure around Kestanbol (modified after Mützenberg, 1997).

The heat flow values (Table 1) calculated based on the RHP are similar to those reported based on field measurements, and CPD estimation reported (Eckstein, 1978; Karat and Aydin, 2004; Akin et al., 2014).

The radioactive heat production (RHP in μW/m^3) by granites has been calculated using the heat generation constant and the uranium, thorium, and potassium concentrations C_U, C_{Th}, C_K using equation suggested by Rybach (1976) and Cermak et al. (1982):

$$RPH = \rho(9.52\ C_U + 2.56\ C_{TH} + 3.48\ C_K) \times 10^{-5}$$

where ρ is the density of rock in kg/m^3; C_U and C_{Th} are the concentration of U and Th in mg/kg, respectively,

Table 1. The heat generation of Kestanbol granites and the heat flow value over the region are based on U, Th, and K content (U, Th, and K contents are from Orgun et al. 2007).

Sample no.	U (ppm)	Th (ppm)	K (wt %)	RHP (µW/m^3	HF (mW/m$^{3)}$
1	11.90	50.00	3.74	6.87	108.67
2	8.20	54.00	3.95	6.21	102.11
3	8.30	62.00	4.14	6.81	108.08
4	17.40	80.00	3.98	10.38	143.76
5	16.10	59.00	3.83	8.58	125.76
6	14.30	62.00	3.92	8.33	123.29
7	15.70	61.00	3.76	8.61	126.05
8	16.30	62.00	4.11	8.86	128.61
9	15.90	59.00	3.92	8.53	125.33
10	14.00	62.00	3.91	8.25	122.51
11	10.70	47.00	3.82	6.36	103.58
12	11.80	58.00	3.88	7.41	114.07
13	10.40	42.00	3.76	5.93	99.30
14	12.60	53.00	3.69	7.25	112.49
15	17.00	47.00	3.49	7.95	119.47
16	9.70	47.00	3.38	6.06	100.59
17	9.60	40.00	3.81	5.59	95.90
18	7.50	43.00	3.69	5.25	92.47
19	12.30	65.00	3.70	8.00	120.02
20	14.10	54.00	3.72	7.71	117.06
21	7.30	36.00	3.56	4..70	86.99
22	11.10	47.00	4.03	6.48	104.80
29	15.40	59.00	3.77	8.39	123.91
32	14.30	65.00	3.88	8.53	125.33
27	9.70	50.00	4.57	6.38	103.78
61	9.90	40.00	3.76	5.66	96.63
62	10.80	63.00	3.67	7.48	114.75

and C_K is the concentration of K in weight percentage in the granites. The surface heat flow values were calculated using the proposed equation by (Lachenbruch, 1968)

$$Q = Q_0 + D \times A$$

where Q is the heat flow at the surface, Q_0 is an initial value of heat flow unrelated to the specific decay of radioactive element at a certain time, D is the thickness of rock over which the distribution of radioactive element is more or less homogeneous, and A is the radioactive heat production. Since the thin crustal thickness (approximately 25km) is observed in the coastal region of the western part of Turkey (Tezel et al., 2013), therefore, the background heat flow value 40 mW/m^2 is considered in the west part of Turkey. Based on the heat flow value, the subsurface temperature has been calculated using the following relation (Vernekar, 1975)

$$Q = \left(\frac{dT}{dZ}\right)$$

where k is the thermal conductivity of the rock and dT/dZ is the geothermal gradient. The surface temperature has been calculated by taking the average surface temperature of about 25 °C (Vernekar, 1975) and thermal conductivity of the granitic rock as 3.8 Wm^{-1}C^{-1}.

6. Stress field status of western Anatolia

The western Anatolian region was under compression due to several collision events from Mesozoic to Early Tertiary, resulting in structural fabric folds and faults. The initial structural fabric was trending NW-SE in the eastern Aegean Sea, changing to E-W and ENE to WNW across the western Anatolian region. The major regional forces act on the western Anatolia northward movement of the African plate, northwest movement of the Arabian plate, and west and SW movement of the Anatolian plate culminating into the Aegean arc in the Aegean Sea west of Turkey (Figure 6).

Western Turkey is an active crustal extension zone. This zone is located south of the North Anatolian Fault Zone (NAFZ) and north of the Aegean subduction zone (Figure 6). The extension due to westward motion of Turkey (strike-slip fault associated with the North Anatolian Fault system, moving at the rate of 36 mm/year) relative to Eurasian is accommodated by the shortening in Aegean subduction zone (McKenzie, 1972, Taymaz et al., 1991, Jackson, 1994)

Detailed stress field analyses were carried out by Rabai et al. (1992) using earthquake focal mechanism, in situ stress measurements (nearly 284 measurements) based on hydraulic fracturing, well blow-outs, over coring, and flat-jack procedure (Rabai et al., 1992) for regions covering the western and eastern Mediterranean region, northern Africa and NW Arabia and the Russian plates. These regions exert forces on the North Anatolian Fault Zone in the northern part of Turkey. Based on the above data Rabi et al. (1992) evolved a regional stress field map for the entire regions. Based on a simple numerical approach to calculate the S_{hmax} and S_{hmin} directions was developed by Rabi et al. (1992). In the Anatolian region, the S_{hmax} is perpendicular to the N-S convergence between the Arabian and Russian plate (Figure 6) and changes progressively from NW-SE (in the east Anatolia) to NE-SE (in the western Anatolia). The stress state changes from compressional in the east to extensional in the west. The Anatolian lateral movement is absorbed by the Aegean trench; a part of this lateral stress is resulting in deformation of the continental blocks present between the Anatolian fault zone and the Aegean trench. This implies that all the rock formations along the western part of the Bagan peninsula are under a compressive stress regime.

7. Discussion

The western part of Turkey is loci of several geothermal provinces represented by hundreds of thermal springs with temperatures varying from 40 to 86 °C. The province

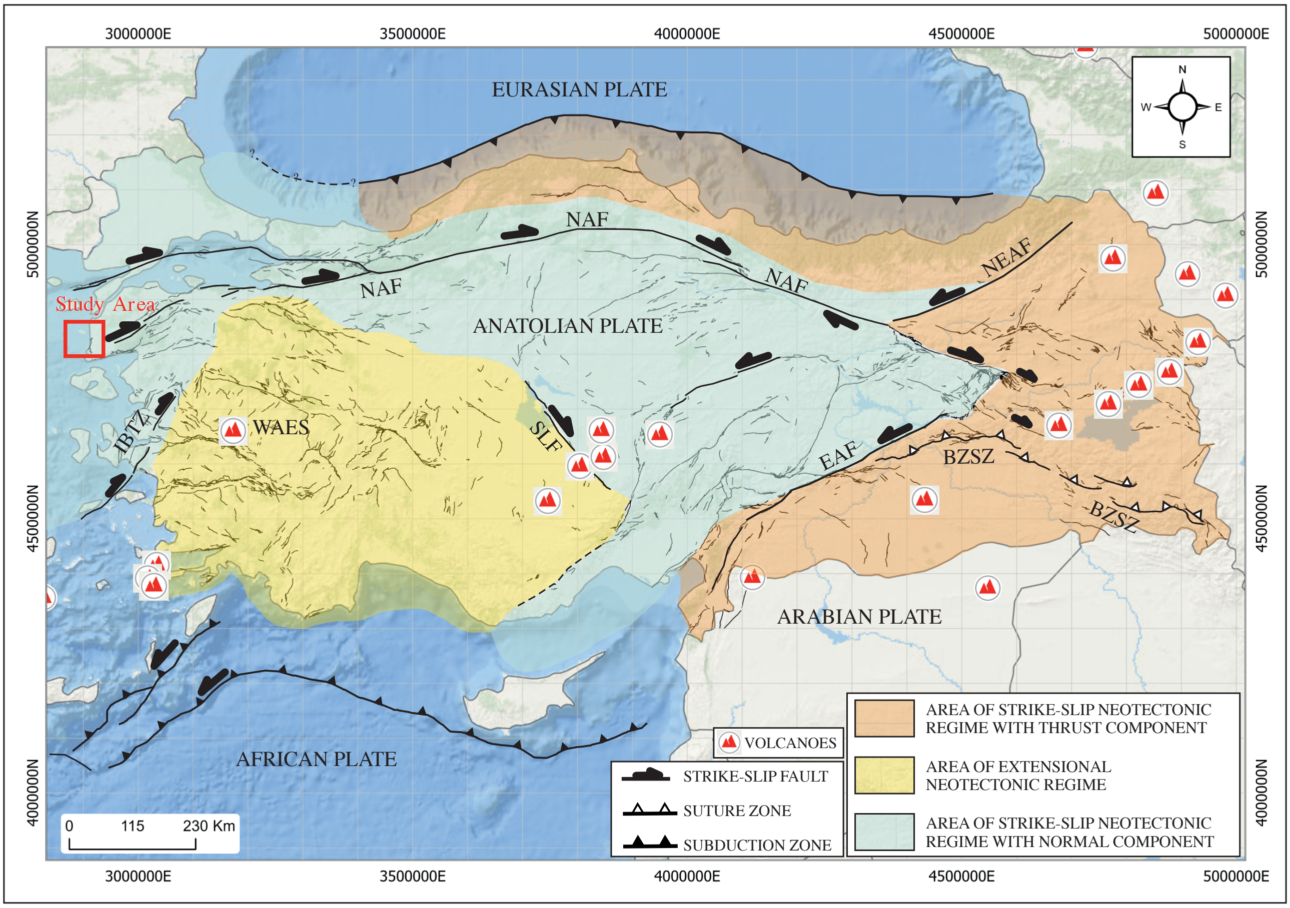

Figure 6. Major regional tectonic regimes over western Anatolia (modified after Sengor and Dyer, 1979); Sengor (1980), Barka (1992), Bozkurt (2001), Kocyigit and Ozacar (2003); modified after from Baba et al. (2021).

that falls within this region includes Kestanbol and Tuzla (Çanakkale). The geothermal manifestations are associated with deep-seated faults, large sedimentary basins, and volcanic sites. This region is also represented by several plutonic rocks of the Miocene age, such as the Kestanbol granitoid. These granitoid, due to their crustal origin, contain a high concentration of radioactive elements (U, Th, and K) due to the presence of minerals such as thorite, zircon, and allanite. The heat generated by the Kestanbol granitoid is 5 to 8 mW/m^2, which is greater than the average heat generated by the granites of 5 mW/m^2. The gamma-ray values in the soils and the air surrounding the Kestanbol granitoid plutons are anomalously high of 9200 nGy/h, and over the Kestanbol granitoid, the value is 880 nGy/h. Besides the natural heat flow conveyed to the surface from the mantle and Aegean subduction zone, this granite also contributes considerable heat to the region. The heat flow values contribution by the Kestanbol granites vary from 99 to 143 mW/m^2 that is similar to the heat flow values measured from the exploration boreholes drilled near Tuzla and estimated from the CPD deduced from aeromagnetic traverses over the western region of Turkey. Such high heat generating granites are the target for initiating enhanced geothermal systems, like the ones operating in Slutz in France. The Kestanbol granitoid is covered by a sequence of Late Miocene volcanic rocks overlain by Pliocene sedimentary sequence. The estimated temperature of the granite at 2 km is about 90 °C and at 3 km depth, it is 120 °C. The Kestanbol granitoid is under a convenient NE-SW $S_{hmax,}$ making it a suitable candidate to initiate the EGS project. A schematic section across NE-SW traverse (from NAF to Aegean trench) is presented in Figure 7.

The Aegean extensional tectonic fabric encloses Anatolide-Tauride and Sakarya continental plates, which collided in the Paleocene. The ophiolites and the blueschists of the Cretaceous were derived from the collision of the above two plates. The plutonic activity resulting from the post-Eocene–Oligocene collision event north of the suture zone marks the oldest magmatic event in this region. This magmatic activity migrated southwards, changing the composition from calc-alkalic to alkalic. The Quaternary volcanism appears to have resulted due to the lithospheric extension and decompressional melting associated with upwelling of the asthenosphere, which has resulted in Quaternary alkaline volcanism in the south central part of the Aegean extensional province (Dilek and Altunkaynak, 2009).

10. Conclusion

The Miocene Kestanbol granitoid, a quartz monzonite intrusion, has an anomalous concentration of U, Th, and K and is one of the high heat generating granites located south of Çanakkale in the western Anatolian region. The Kestanbol granitoid is a product of crustal melting and intruded into the older metamorphics and younger volcano-sedimentary sequence of pot Miocene-Pliocene sequence. The presence of high-temperature geothermal

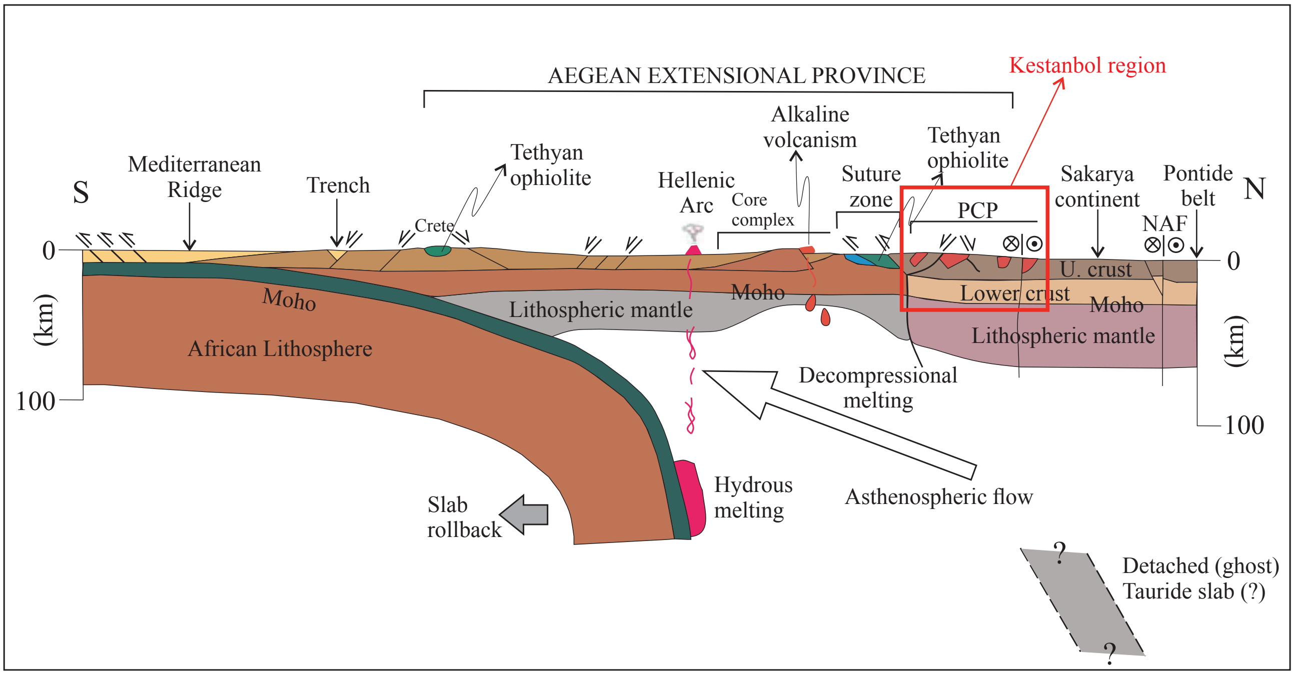

Figure 7. Interpretative tectonic cross section along a NNE-SSW-trending profile through the Africa-Eurasia convergence zone and the Aegean extensional province (modified after Dilek and Altunkaynak, 2009).

systems in this province, together with high-temperature bottom hole temperatures recorded from the exploratory drill hole and suitable temperature of the granite at 3 km depth and convenient stress fields, makes this granite a suitable candidate for initiating enhanced geothermal systems projects.

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