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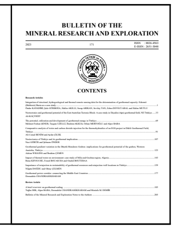

Neotectonics of Türkiye and its geothermal implication

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ABSTRACT

Favorable conditions for geothermal energy were created in Türkiye during its neotectonic episode from Neogene to Quaternary. This episode is characterized mainly by fluvio-lacustrine sedimentation and strike-slip tectonics with associated magmatism. Under these conditions, a great number of geothermal areas have formed in the neotectonic provinces in association with major tectonic features, including the North and East Anatolian Fault Zones (NAFZ and EAFZ, respectively). Today, the geothermal resources of Türkiye are mainly located in the West Anatolian Extensional Province associated with the graben systems. However, the Central Anatolian Ova Neotectonic Province is considered one of the most promising geothermal targets which are characterized by the presence of widespread hot dry rock systems. This study mainly aims to throw light on the possible potentiality of these resources at Kırşehir Block by emphasizing the neotectonic evolution of the country.

1. Introduction

Geothermal energy is natural heat that can be extracted from the earth. The earth's interior is hot and temperature increases with increasing depth. The increase is about 30 ºC per km of depth (1 ºC per 33 m of depth). The relationship between the variation in temperature and depth is called the geothermal gradient (Nwankwo and Ekine, 2009; Kwaya et al., 2019). The geothermal gradient may show regional variations depending on geological conditions. In areas where there are active tectonism and volcanism, the geothermal gradient is much higher than in other areas. Such areas are known as geothermal areas where more earth's internal heat is transferred to shallow depths or surfaces by conduction or convection mechanisms. The former mechanism is the transfer of heat by means of molecular action within the earth's crust, whereas the latter involves fluid movements. Conductively heated geothermal areas are generally represented by hot dry rocks where there is no sufficient geothermal fluid to transport heat to the surface. Such geothermal resources are exploited by creating an artificial reservoir in these hot rocks at depth so that water can be pumped into them at the surface. Convectively heated geothermal areas have adequate hot fluids to rise close to the surface (Rybach, 2010).

Importance of the geothermal energy increases in the world every day. The main reasons for this are related to global energy crises and climate change. Climate change is caused by the emission of greenhouse gases, mostly carbon dioxide and methane. Burning fossil fuels for energy production creates most of these emissions. Greenhouse gases lead to global

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warming and thus to climate change. Climate change has already started in the world and perhaps will result soon in an expansion of deserts, wildfires, storms, droughts, glacial retreats, sea-level rise, flooding, etc. Climate change threatens people with food, water scarcity, disease, economic loss, human migration, etc. Deep cuts in the emission of greenhouse gases are vital and require switching from using fossil fuels to green energy resources. Geothermal energy is one of the green energy resources. It doesn't much create carbon dioxide during production, but it can emit a slight amount of greenhouse gases and air pollution. It will likely play a huge role in Türkiye in the transition to renewable energy because the thermal energy stored in the shallow earth crust of this country may be enough to provide a major part of its energy demand. Today, Türkiye is ranked 4th in the world in terms of installed geothermal capacity, but effective geothermal investigations and explorations may promote her to the first division (Miranda-Barbosa et al., 2017).

2. Geothermal Systems

Geothermal systems are hot petrological features at shallow depths with three primary components: a heat source, reservoir rock, and cap rock. The heat source is dominantly characterized by a volcanic intrusion or shallowly emplaced magma in volcanically and tectonically active areas. These conditions make a large heat transfer from deep in the Earth to relatively shallow depths where usually convective circulation of ground waters takes place. Reservoir rock is actually a hot rock with or without porosity and permeability. If it is permeable and fractured, it may contain fluid and allow it to flow into the production wells. Cap rocks are impermeable rocks above the reservoir rocks. They trap and prevent the loss of the fluid that exists in the reservoir rocks. As understood from the description above, fluid is not a primary component of a geothermal system. Geothermal energy may be present in a geothermal system even with no permeable reservoir or circulating fluid. Such a system is known as hot-dry rock. In this system, the impermeable rocks above the heat source are heated to extremely high temperatures through an abnormally high conductive heat flow. Utilization of the system can be done only after creating an artificial geothermal reservoir by using hydro-fracturing to form or enhance permeability and porosity in the hot rocks. To make energy production, two wells (one injection and one production) must be drilled into the hot rock. Hot dry rock resources seem virtually unlimited in magnitude but only those at shallow depths are preferable because the production cost of energy from this system is higher than that of conventional geothermal systems. However, the advent of new technologies for drilling and production may improve its economics in the near future (Mortensen, 1978; Stefansson, 2000; Duchane and Brown, 2002; Saemundsson et al., 2009; Çiçek, 2020).

From the description above, it is clear that geothermal systems form where active tectonics and magmatism prevail. Such conditions were created in Türkiye in the middle Miocene and have been ruling since then. This period represents the neotectonic phase of the country and without its detailed knowledge, it is not possible to evaluate the geothermal potential of Türkiye. Therefore, this topic will be dealt with first in the following paragraphs.

3. Neotectonics of Türkiye

Neotectonics of Türkiye was established in the middle Miocene after the closure of the southern branch of the Neo-Tethys Ocean (Bitlis Ocean) along the Bitlis-Zagros Suture Zone in Southeast Anatolia. Following the closure, Eastern Anatolia started to be squeezed between the Arabian and Eurasian plates, leading to a progressive thickening and shortening of the crust and forcing an Anatolian wedge (Anatolian Plate) to move westward away from the high-strain area. This movement took place along two major strike-slip fault zones, the dextral North Anatolian and the sinistral East Anatolian Transform Faults, NAFZ and EAFZ, respectively (Figure 1). It led to the deformation and oblique overthrusting of the Anatolian Plate onto the oceanic lithosphere of the Mediterranean along the Hellenic-Cyprus subduction zone.

It was the main cause of the formation of the neotectonic provinces of Türkiye, including East Anatolian Contractional, Central Anatolian Ova, West Anatolian Extensional, and North Anatolian Provinces (Figure 2).

The neotectonic regime had very profound effects on the geological evolution of Türkiye during the

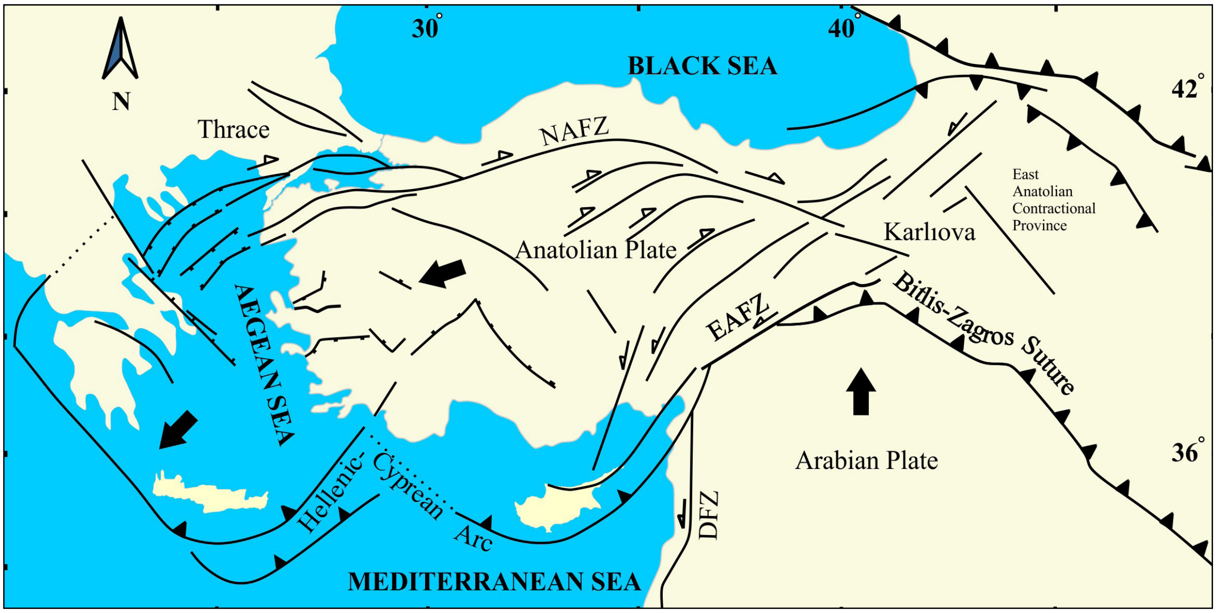

Figure 1- Neotectonics of Türkiye (modified from Gürer et al., 2003; NAFZ: North Anatolian Fault Zone, EAFZ: East Anatolian Fault Zone, Dead Sea Fault Zone).

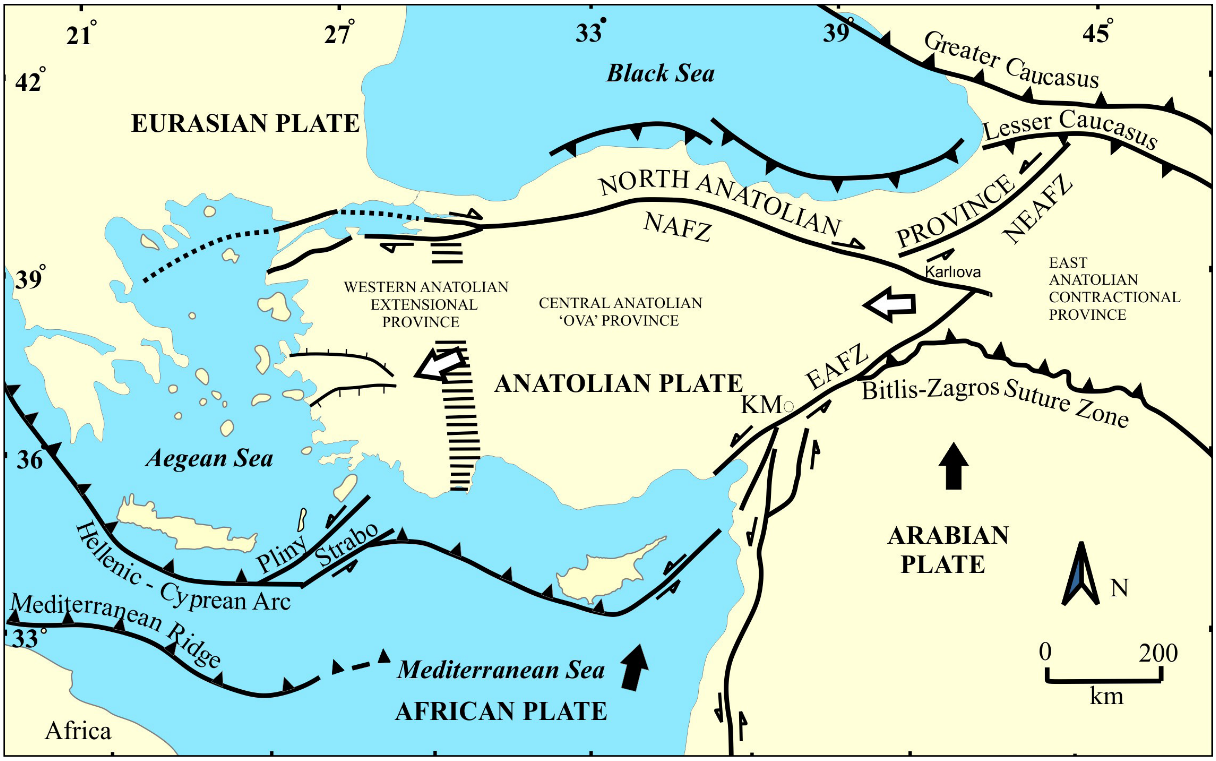

Figure 2- Neotectonic provinces of Türkiye (modified from Bozkurt, 2001; NAFZ: North Anatolian Fault Zone, NEAFZ: Northeast Anatolian Fault Zone, EAFZ: East Anatolian Fault Zone, KM: Kahramanmaraş).

Neogene to Quaternary. It was dominated in the neotectonic provinces by extension and strike-slip faulting with widespread continental sedimentation and calc-alkaline magmatism. Closure of the Bitlis Ocean resulted in the East Anatolian Contractional Province crustal thickening and generation of many compressional and extensional structures, such as east-west trending thrust, reverse, and strike-slip faults with associated ramp basins. The westward motion of the Anatolian Plate caused in the eastern part of the Central Anatolian Ova Province internal deformations and the formation of many second-order faults and associated basins, arising from the NAFZ. In the rest of this province, a strike-slip dominated ova regime became established. Ovas are extensional basins bounded by dextral or sinistral oblique-slip faults. In the West Anatolian Extensional Province, the extensional regime has been established due to the obstruction of the westerly motion of the Anatolian Plate both by the abrupt south-westerly bend of the NAFZ in the Marmara Region and the Grecian mainland. The North Anatolian Province is tectonically the quietest region among the others and appears to be undergoing E-W shortening with a number of strike-slip faults with strong E-W thrust components (Şengör, 1979, 1980; Şengör and Yılmaz, 1981; Özgül, 1984; Görür et al., 1984; Şengör et al., 1985; Görür and Tüysüz, 2001; Bozkurt, 2001; Gürer et al., 2003; Okay, 2008).

4. Neotectonic Provinces of Türkiye

The neotectonic provinces developed on top of the different palaeotectonic terrains of Türkiye that had mostly formed a united land mosaic before the elimination of the Bitlis Ocean. Each of the neotectonic provinces has a distinctive set of structures and stratigraphy with characteristic tectonism and magmatism (Şengör et al., 1985; Bozkurt, 2001; Okay, 2008). Their Neogene stratigraphy is more or less similar but the pre-Neogene stratigraphy is different because it developed when the terrains were separate blocks and undergoing different tectono-stratigraphic evolution. Unless the pre-Neogene stratigraphy of the palaeotectonic terrains is understood, it is difficult to evaluate their geothermal potential because, in most of the geothermal fields in Türkiye, the pre-Neogene formations constitute the reservoir rocks. Therefore, the pre-Neogene stratigraphy of each province is summarized below first and then their Neogene stratigraphy is discussed collectively.

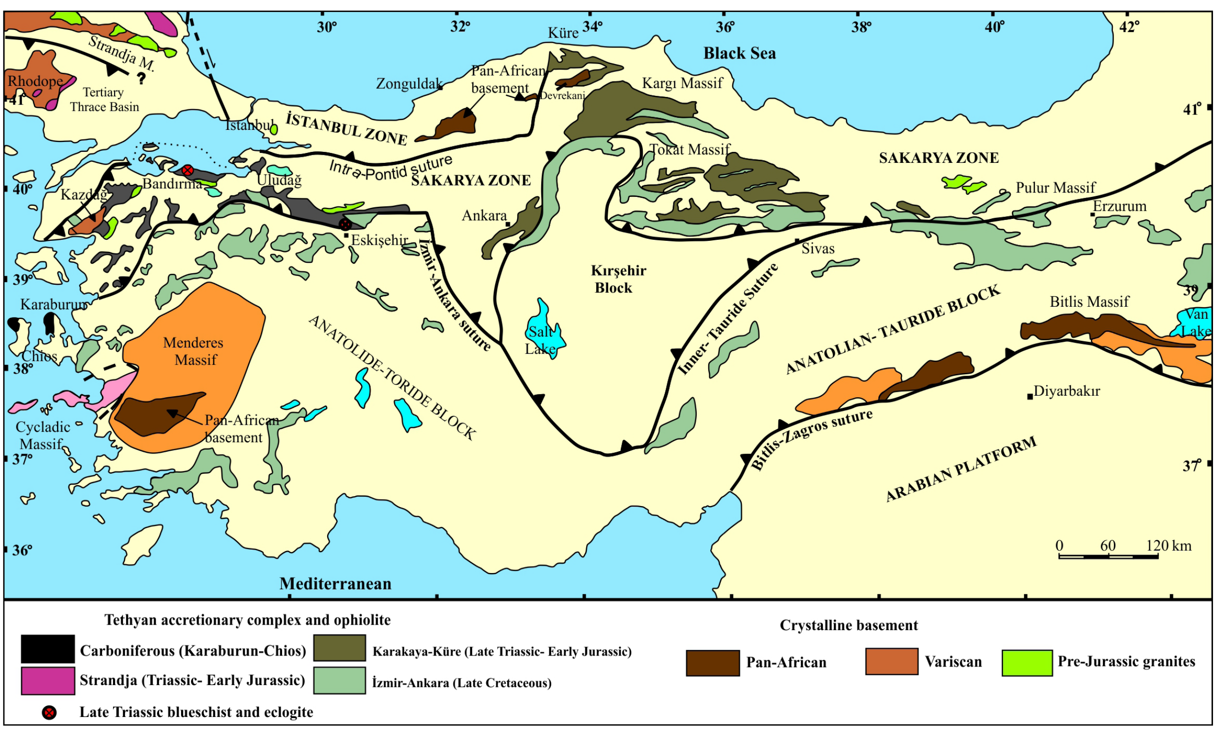

Figure 3- Palaeotectonic terrains of Türkiye (modified from Okay, 2008).

4.1. East Anatolian Contractional Province

This province covers Southeast and East Anatolia and developed on two palaeotectonic terranes of Turkey, namely the Arabian Platform and East Anatolian Accretional Complex (Figures 2 and 3). The Arabian Platform has a Pan-African type basement overlain with an angular unconformity by a sedimentary sequence, ranging in age from Cambrian to Tertiary. The pre-Permian sediments of the sequence are composed mainly of clastic rocks, whereas the post-Permian deposits consist of carbonates. Eastern Anatolia is characterized by a basement, comprising an ophiolitic accretional melange of Upper Cretaceous age. This basement is unconformably overlain by Palaeocene to Eocene flysch and olistostrome that shallow upward and pass into Neogene continental deposits with widespread calc-alkaline volcanics (Şengör and Yılmaz, 1981; Perinçek, 1990; Yılmaz, 1993; Okay, 2008).

4.2. Central Anatolian Ova Neotectonic Province

This province has developed dominantly on Kırşehir Block, one of the main palaeotectonic terrains of Türkiye (Figures 2 and 3). The Kırşehir Block consists of a metamorphic basement and cover rocks. The metamorphic basement comprises gneisses, micaschists, metaquartzites, and marbles, whereas the cover rocks include partly preserved Upper Cretaceous ophiolite nappes and sedimentary rocks of Upper Cretaceous to Neogene age. Both the metamorphic basement and the ophiolite nappes are intruded by Cretaceous granite intrusions (Beyazpirinç et al., 2022). Ophiolite nappes are comprised of basalt, radiolarian cherts, pelagic limestones, sandstones, and serpentines. Sedimentary rocks mostly represent the sediments that accumulated in the magmatic arc or collision-related basins of various sizes developed both on the metamorphic basement and the ophiolite nappes. The magmatic arc-related basins include Çankırı, Kırıkkale, Tuzgölü, Ulukışla, and Şarkışla, whereas the collision-related ones comprise Refahiye, Sivas, Yıldızeli, and Yozgat-Sorgun Basins. The formers formed during the Cretaceous and the latter during the Eocene. Both types of basins dominantly accumulated turbidites until the Oligocene when they were obliterated and turned to constitute the neotectonic cover of the Central Anatolian ova regime (Şengör and Yılmaz, 1981; Şengör et al., 1982; Seymen, 1983; Görür et al., 1995*a, b*, 1998; Poisson et al., 1996; Yalınız et al., 2000; Görür and Tüysüz, 2001; Whitney and Hamilton, 2004; Okay, 2008).

4.3. West Anatolian Extensional Neotectonic Province

The basement of this province is characterized by the Sakarya Zone and the Anatolide-Tauride Block which were amalgamated into a single land mosaic after the closure of the Neo-Tethys Ocean along the İzmir-Ankara Suture (Figures 2 and 3). The Sakarya Zone is characterized in its lower part by strongly deformed and locally metamorphosed Paleo-Tethyan active continental margin units, ranging in age from Permian to Triassic. These units form a stratigraphic basement for a sedimentary sequence, ranging in age from Lower Jurassic to Eocene. The Paleo-Tethyan basement rocks comprise metabasite-marble-fillat series with exotic eclogite and bluschist lenses, passing upward across a tectonic contact into Triassic clastic and basic volcanic rocks with abundant Carboniferous and Permian exotic blocks, including shallow-water carbonates, basalts, and radiolarian cherts. This basement is unconformably overlain by Lower to Middle Jurassic molasses sandstones and rift volcanics, grading upward into Upper Jurassic to Lower Cretaceous limestones and then into Upper Cretaceous to Eocene flysch with volcanic interbeds (Şengör et al., 1984; Okay et al., 1991, 1996). In the northern parts of the central and the eastern Pontides, the Cretaceous to Eocene units constitute the Neotethyan magmatic arc and the southern passive continental margin of the Black Sea, opening as a back-arc basin behind the magmatic arc (Yılmaz and Boztuğ, 1986; Okay et al., 1994, 2002, 2006; Görür, 1997; Görür et al., 1997). Eocene rocks pass upward in places into Oligocene-Neogene fluvio-lacustrine deposits.

The Anatolid-Tauride Block shows complex stratigraphic, structural, and metamorphic features. It has a thick sedimentary sequence sitting on a Pan-African crystalline basement above an angular unconformity. The sequence consists of Palaeozoic continental to inner shelf clastic and carbonate rocks in the lower part and Triassic to Upper Cretaceous carbonates in the upper part. The block seems to have stayed as a carbonate platform until the closure of the Neo-Tethys Ocean between the Cretaceous and

Palaeocene. During the elimination of the ocean, the Anatolide-Tauride Block was subjected to strong deformation, ophiolite obduction, thrusting, and regional metamorphism. The major metamorphic zone of the block is the Menderes Massif, a Barrovian-type metamorphic belt. It has a pre-Cambrian core of micaschists, gneiss, granulite, and eclogite intruded by metagranites. This crystalline basement is succeeded by metasedimentary cover rocks of Palaeozoic to Lower Tertiary age. The lower part of the cover sequence consists mainly of quartzite, phyllite, and marbles of the Permo-Carboniferous age, passing upward into Triassic to Cretaceous carbonates, mainly marbles. Above the marbles are red pelagic recrystallized limestones overlain by a slightly metamorphosed flysch sequence with serpentine blocks. This flysch sequence is tectonically overlain by various nappes of the Anatolide-Tauride Terrains, i.e. Lycian Nappes and Bornova Flysch (Özgül, 1984; Şengör et al., 1984; Okay, 1984, 2008; Okay et al., 1996). Neogene rocks rest on top of the pre-Neogene units above an angular unconformity and constitute fluvio-lacustrine sediments with calc-alkaline volcanics deposited mainly in grabens (Şengör et al., 1985).

4.4. North Anatolian Neotectonic Province

The basement of the North Anatolian Province consists of three different terranes, namely Strandja, İstanbul, and Sakarya Zones (Figures 2 and 3). Pre-Neogene stratigraphy of the Sakarya Zone is already given above. The pre-Neogene stratigraphy of the Strandja and the İstanbul Zones is as follows: The Strandja Zone starts at the base with Permian metamorphic rocks intruded by granitoids. The metamorphic rocks are overlain with an angular unconformity by a metasedimentary sequence of the Triassic to Jurassic age; Triassic rocks comprise continental to shallow-marine clastic and carbonate rocks, passing upward across an angular unconformity into clastic sediments of Jurassic age. The metasedimentary sequence is succeeded tectonically by melange or un-conformably by Cenomanian conglomerates and neritic limestones followed by Senonian arc-related magmatic rocks (Moore et al., 1980; Chatalov, 1988; Okay et al., 2001; Sunal et al., 2006; Okay, 2008). In the Thrace, this sequence is overlain by the infill of the Thrace Basin. The infill ranges in age from Middle Eocene to Pliocene and is dominated by a shallowing upward and dominantly clastic succession. The Middle Eocene to Lower Oligocene sediments are represented in the deeper part of the basin by tuffaceous turbidites and on the margins by continental to shallow-marine clastics, volcanoclastics and carbonates. Post Lower Oligocene sediments are mainly brackish to terrestrial in nature. The pre-Oligocene rocks of the infill of the Thrace Basin accumulated in the arc-related basinal setting above the northward subducting Intra-Pontide Ocean, whereas post-Oligocene rocks developed in a dextral strike-slip shear zone, constituting the widest part of the North Anatolian Shear Zone extending between the East Anatolia and the Aegean (Görür et al., 1984; Görür and Okay, 1996; Şengör et al., 2005; Siyako and Huvaz, 2007; Görür and Elbek, 2013).

The İstanbul Zone is represented by an Ordovician to Quaternary thick sedimentary sequence, sitting with an angular unconformity on top of a Late Pre-Cambrian crystalline basement. The crystalline basement is characterized by gneiss, amphibolite, metavolcanics, metaophiolite, and granitoids. The sedimentary sequence on the basement shows marked stratigraphic differences along the length of the zone. In its western part, Ordovician rocks comprise continental clastics of arkosic nature, passing upward into Silurian quartzites and overlying shales. The shales are succeeded by Devonian reefal limestones, grading up into interbedded shales and cherty limestones of the same age. On top of them are Carboniferous radiolarian cherts and siliciclastic turbidites. The turbidites are unconformably overlain by Triassic rocks. Triassic rocks consist at the base of red sandstones with basaltic volcanic interbeds, passing upward into shallow- to deep-marine limestones and siliciclastic turbidites. The Triassic series are succeeded across an angular unconformity by Upper Cretaceous-Palaeocene clastic, carbonate, and andesitic volcanic rocks. In the European side of İstanbul, Palaeozoic rocks are unconformably overlain by Eocene and Neogene sediments. Eocene sediments comprise reefal limestones and marls, passing upward across an angular unconformity into the Neogene sediments represented mainly by fluvio-lacustrine clastic with tuffaceous interlayers. In the eastern part of the İstanbul Zone, around Zonguldak, the sedimentary sequence displays different stratigraphic development for certain periods. For instance here, the Devonian neritic carbonates pass upward into deltaic clastic rocks of the Carboniferous with coal seams. These sediments are unconformably overlain dominantly by continental red clastics of the Permian age succeded with a transitional contact by Triassic lacustrine marl, clays, mudstone, and limestone. On contrary to the western part, the Jurassic is present here and is represented by Middle and Upper Jurassic rocks, grading upward into Cretaceous neritic carbonates. Middle Jurassic rocks are coal-bearing deltaic clastics at the base, grading upward into deep-water siliciclastic turbidites and then back into the deltaic sequence again. Upper Jurassic rocks are mostly characterized by thick neritic carbonates, extending in age up to Aptian. These shallow-water carbonates are succeeded by a sequence of Aptian to Eocene age, representing the passive continental margin sediments of the Western Black Sea Basin. The sequence consists predominantly of volcanogenic coarse clastic rocks, shales, and carbonates with a deepening upward character. The volcanoclastic rocks are mostly turbidites with huge exotic blocks. The neotectonic Miocene sedimentary cover of the eastern part of the İstanbul Terrain comprises dominantly fluvio-lacustrine sediments and overlies the Eocene rocks with an erosional contact (Okay et al., 1994; Görür, 1997; Ustaömer et al., 2005; Okay, 2008; Hippolyte et al., 2016; Tüysüz, 2022).

4.5. Neogene Stratigraphy of the Neotectonic Provinces

In the East Anatolian Contractional Neotectonic Province (Figure 2), the sediments characterizing the neotectonic episode accumulated in various basins, such as Muş, Ahlat-Adilcevaz, Karayazı-Tekman, Kağızman-Tuzluca, and Erzurum-Pasinler-Horasan basins. These basins are generally ramping, intermountain, and pull-apart in nature and contain sedimentary successions, ranging in age from Middle Miocene to the Pliocene age. Middle Miocene units are spatially limited and have a regressive sequence, starting with shallow marine sediments at the base and lagoonal facies at the top. They consist of clayey limestone, marl, sandstone, and siltstone in part with volcanic rocks, such as basalt, trachyte, andesite, and pyroclastic rocks. The Middle Miocene rocks pass upward across an unconformity into a continental Upper Miocene sequence that is characterized by sandstone, siltstone, and conglomerate in the lower part and clayey limestone, tuff, agglomerate, and lava in the upper part. The Pliocene rocks in the region are comprised of fluvio-lacustrine sandstone, siltstone, conglomerate, marl, and limestone associated with basalt, andesite, and trachy-andesite (Irrlitz, 1972; Şaroğlu and Güner, 1981; Güner, 1984; Şengör et al., 1985; Şaroğlu and Yılmaz, 1986).

In the Central Anatolian Ova Province (Figure 2), the Neogene sediments were deposited in two types of basins: Ova and strike-slip fault-related basins. Ovas are large, roughly equant extensional basins bounded by more than two oblique-throw faults (Şengör, 1980; Şengör et al., 1985). These basins contain widespread gypsiferous series deposited in fluvio-lake environments together with clastic and volcanic rocks. Strike-slip basins formed in association with the EAFZ, forming the eastern boundary of the province. These basins include Karlıova, Bingöl, and Lake Hazar (Hempton et al., 1983; Aksoy et al., 2007). The Adana Basin, which is associated with the western end of the EAFZ, is not a strike-slip basin. It formed as an incompatibility gap associated with displacements around the triple junction in the vicinity of Kahramanmaraş (Şengör et al., 1980, 1985). During the neotectonic episode, all the strike-slip basins accumulated Miocene to Pliocene sediments, comprising fluvio-lacustrine clastic and carbonate rocks with tuff, tuffite, agglomerate basalt and andesitic basalt (Yalçın and Görür, 1984; Okay, 2008).

Neotectonic cover rocks of the West Anatolian Extensional Neotectonic Province (Figure 2) are characterized by fluvio-lacustrine sediments and associated magmatic rocks of the Upper Oligocene to Quaternary age. Their Upper Oligocene to Lower Miocene part was deposited in large interconnected lake basins, covering almost the whole province, whereas the rest was confined to the graben systems. The most known graben structures are east-west oriented Gediz, Küçük Menderes, Büyük Menderes, and Kerme grabens. In their sediments rich borate, sodium sulphate, lignite, and clay are found. The associated magmatic rocks comprise both intrusive and extrusive rocks. Intrusive rocks are mostly characterized by granodiorites and monzonites, whereas extrusive rocks display a large variety of composition, including basaltic andesite, andesite, trachyandesite, latite, and dacite (Helvacı, 1995; Yılmaz, 1997; Görür et al., 1995*a, b*; Aldanmaz et al., 2000; Yılmaz et al., 2001).

The North Anatolian Neotectonic Province (Figure 2) is characterized by very weak active tectonism. Besides the Thrace Basin, considerable depositional areas in this province during the neotectonic period (Neogen) are absent. The Thrace Basin formed in the dextral North Anatolian Shear Zone and accumulated during this period mostly fluvio-lacustrine coal-bearing clastics and carbonates in part with tuffaceous material (Görür and Okay, 1996; Görür and Elbek, 2013). Along the southern boundary of the province, there are many sedimentary basins of various sizes formed in the NAFZ. These basins, from west to east, are Gelibolu, Yalova, Gölcük-Derince, Adapazarı, Düzce, Bolu, Çerkeş-Kurşunlu, Tosya, Kargı, Vezirköprü, Havza-Lâdik, Taşova-Erbaa, Niksar, Suşehri, Refahiye, and Erzincan basins. The basins developed in an autonomous boundary region between the North Anatolian, West Anatolian Extensional, and Central Anatolian Ova Neotectonic provinces, and therefore they cannot be considered to belong to any of these provinces. They developed as pull-apart, compressional ramp, transtensional, and fault-wedge basins and accumulated during the neotectonic phase of limnic and fluviatile sediments with volcanic interbeds. Limnic sediments are comprised of marls and limestones in part with interbedded fine clastics and volcanics. The volcanics are mostly calc-alkaline in nature and range in composition from basaltic andesite to rhyolite. Fluviatile sediments are composed of conglomerates, sandstones, and mudstones locally with tuffs and tuffites. All these continental sediments may contain vertebrate, ostracode, spores, and pollen fossils (Tatar, 1975, 1978; Seymen, 1975; Şengör and Yılmaz, 1981; Barka, 1985; Şengör et al., 1985; Görür et al., 1995*b*).

5. Geothermal Potential of the Neotectonic Provinces

In order to judge the geothermal potential of the neotectonic provinces of Türkiye, their palaeotectonic and neotectonic settings, litho-stratigraphy, geological structures, and heat flow must be taken into account. Besides the heat flow, all these features were already outlined in the preceding paragraphs. The heat sources of the provinces are discussed below on the basis of the temperature distribution map of Türkiye at depth of 1000 m prepared by Başel et al. (2013) according to the kriging geostatistical method (Figure 4).

5.1. East Anatolian Contractional Province

In the East Anatolian Contractional Province, temperature distribution at 1000 m below the surface ranges between 40°C and 80°C. In the southeastern

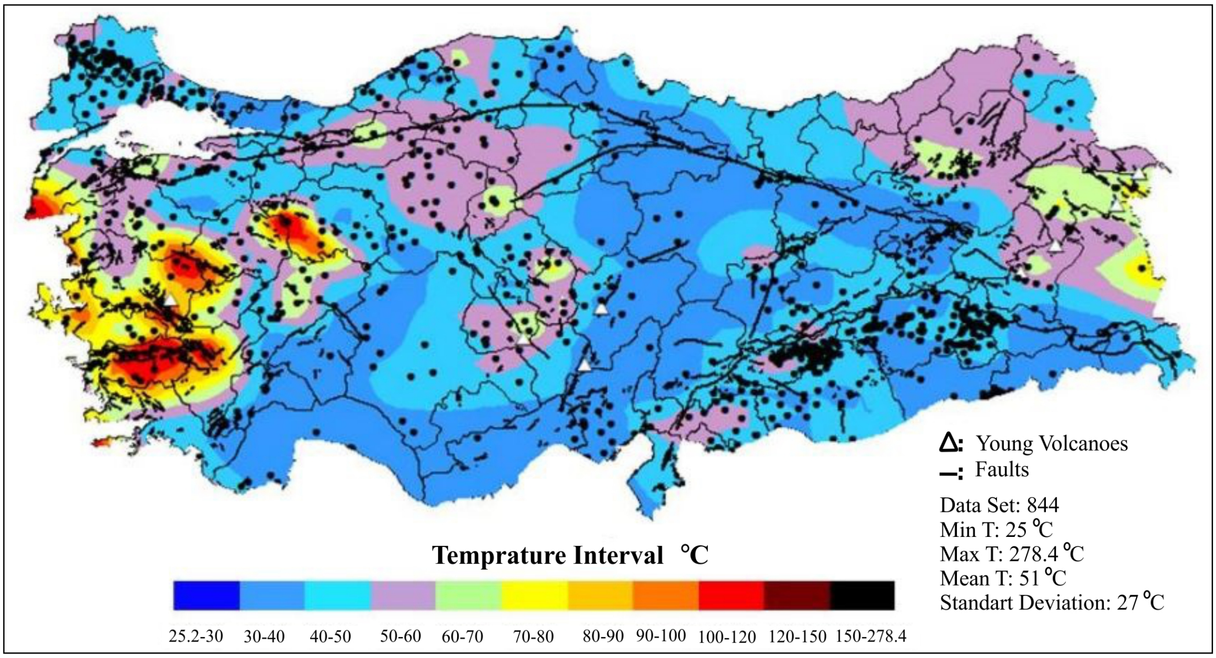

Figure 4- Temperature distribution map of Türkiye at 1000 m below the surface (after Başel et al., 2013).

part of the province, the temperature at the same depth is low and generally varies from 30°C to 50°C. Here, it only reaches 60°C around Gaziantep and Adıyaman, situated along the EAFZ (Figure 4). In the eastern part of the province, the temperature at the same depth is about 50°C to 60 °C but in the vicinities of Erzurum, Ağrı, Bitlis, and Van, it may rise up to 80°C. Geothermal fields are quite common in the province and are found in Ağrı-Diyadin, Bitlis-Nemrut, Van-Erciş, Diyarbakır-Çermik, Şanlıurfa-Karaali-Kabahaydar, Adıyaman-Çörmük-Besni, Gaziantep-Areban-Kartalköy, Batman-Çermik, Şırnak-Beytüşşebap-Besta, Batman-Taşlıdere, Mardin-Ulusu and Siirt-Billoris (Figure 5). Development of these geothermal fields was of course controlled by both the tectonism and the magmatism that prevailed in the province during the neotectonic period. During this period, the East Anatolian Contractional Province underwent N-S contraction and as a result of this E-W trending folds, thrusts, and continental ramp basins developed in the north and south of the region. The middle part of the province has been the site of strike-slip faults and associated basins. Related to these neotectonic activities, a widespread calc-alkaline volcanism also took place in the province until the historical times. The youngest volcanoes in the province are Süphan, Nemrut, Karaca, Tendürek, and Ağrı. Because of the coeval tectonism and magmatism, the geothermal potential of the province must be high. Especially, transtensional and pull-apart areas of the strike-slip faults may be good targets for geothermal explorations. Present-day hot water springs appear to be located in such places. Compressional structures in the province, such as the transpressional part of the strike-slip faults, ramp basins, and the Bitlis-Zagros Suture Zone must be handled carefully in terms of geothermal expeditions. However, in southeast Anatolia, joints, fractures, and folds formed parallel with the orientation of shortening of the province may be favorable places for geothermal resources. Of course, younger volcanoes are another attractive target for investors in geothermal energy. These recent volcanoes may hide very productive geothermal systems beneath their lavas and pyroclastics in the region. Abundant hot water springs around the Ağrı may be an indication of this (Figure 5) (Mutlu and Güleç, 1998; Bektaş et al., 2007; Ulusoy et al., 2008; Baba et al., 2010; Başel et al., 2013; Alacali, 2018; Çırmık, 2018; Bilim et al., 2018).

5.2. Central Anatolian Ova Neotectonic Province

Temperature variation in this region 1000 m below the surface is dominantly between 30°C and 50°C. Although around Çorum, Çankırı, Bolu, Ankara, and

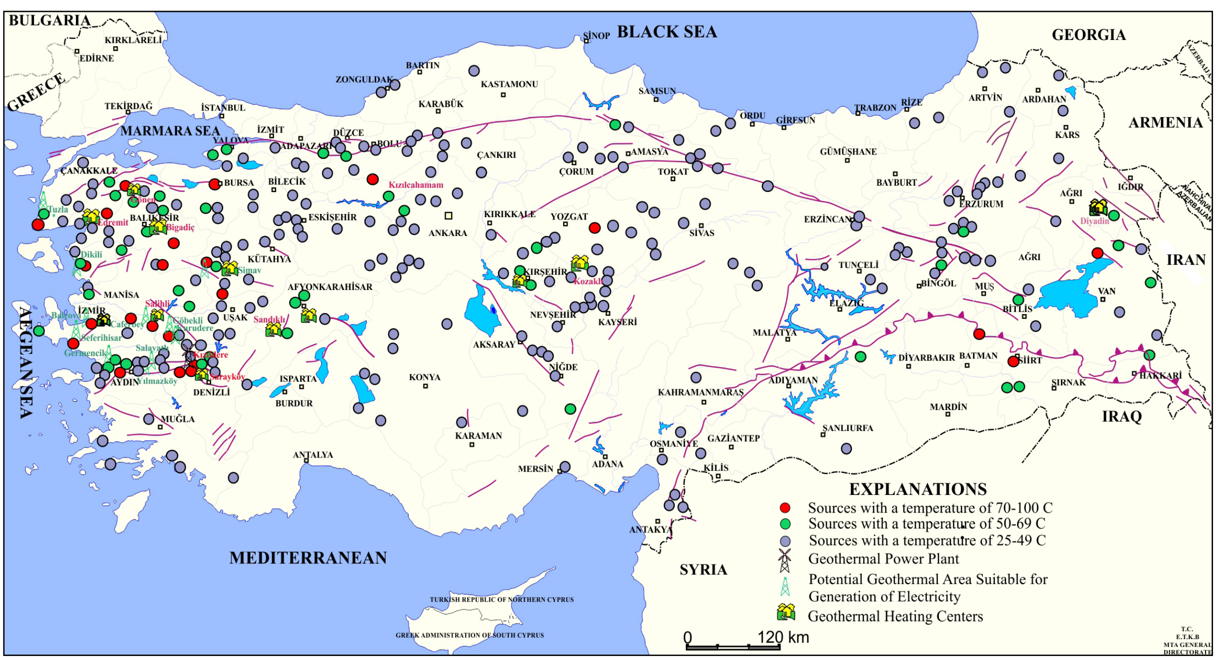

Figure 5- Distribution of geothermal springs in Türkiye (modified from MTA Geothermal Map, 2022).

Kırıkkale, near the NAFZ, it ranges from 50°C to 60°C (Figure 4). Comparable temperatures are also seen at this depth in the Cappadocia region in the south, around Nevşehir, Aksaray, and Niğde where most of the geothermal fields of the province are found. Some of these fields are Kırşehir-Terme, Nevşehir-Kozaklı, and Aksaray-Ziga (Figure 5). Although the geothermal fields may give an idea about the heat flow in this province, the temperature at depth of more than 1000 m is much higher in the Cappadocia. In the Sivrihisar-3 well drilled here by the 3S Kale Energy Company, 294ºC temperature was measured at 3800 m depth. This is the highest temperature measured at this level up to now in Türkiye. Like the Cappadocia, other parts of the Central Anatolian Ova Province seem to be hot at depth as indicated by the existence of many hot water springs and thermal fields in Niğde, Sivas, and the EAFZ, delimiting the province from the east. Along the EAFZ, thermal springs commonly occur in Bingöl, Tunceli, Kahramanmaraş, and Osmaniye (Figure 5). The reason for the elevated temperature in the interior of the Kırşehir Block must be related to its magmatic evolution. Magmatism was very active and common during both palaeo- and neotectonic evolution of this terrain. The neotectonic volcanics are observed in Afyon, Kırka, Konya, Nevşehir, Kayseri, Ankara, Isparta, Karaman, Ceyhan, Hasandağ, Acıgöl, and Erciyes. Actually, volcanoes such as Hasandağ and Erciyes continued their activities up to the historical times. These volcanic activities probably enhanced the geothermal potential of this province and perhaps created common geothermal systems in the region. Besides the volcanism, when the Anatolian Plate started its westward motion during the neotectonic episode, the Central Anatolian Ova Neotectonic Province was deformed and cut into slices by various strike-slip fault branches of the North Anatolian Fault Zone. These faults, of course, must have increased porosities and permeability in the province and thus facilitated the convective and conductive heat transfers to the upper levels. However, up to now, this region unfortunately has not been investigated as much as it deserves. There is a rumour going around that there are not enough fluids in this province at depth. Even so, if this region is much hotter than the rest of Türkiye, it may form attractive petro-thermal geothermal systems (hot rock/dry rock systems). These systems are human-made structures to exploit the earth's crust's heat that contains no fluids in place; therefore, most of their reservoir parameters can be controlled for optimum productivity. Testing and experiences in various countries have proved beyond a doubt that it is technically feasible to recover enough amounts of thermal energy from these systems. The techniques for constructing such artificial reservoir systems are still in the developing stage but surely they will become soon common knowledge worldwide (Mortensen, 1978; Duchane and Brown, 2002; Ateş et al., 2005; Brown, 2009; Başel et al., 2013; Kıyak et al., 2015; Bilim et al., 2017; Şener and Baba, 2019; Aydemir et al., 2019).

5.3. West Anatolian Extensional Neotectonic Province

In this province, crustal extension and magmatism have taken place coevally during the neotectonic episode. Owing to the N-S extension, the crust in western Anatolia is thinned by the formation of graben structures with various sizes and orientations. The grabens have created relatively narrow zones of lower lithospheric thinning and mantle upwelling, thus increasing the geothermal gradient in the region. As seen in Figure 4, this region is the hottest part of the country at least 1000 m below the surface. In large part of the region, the temperature at this depth varies from 50°C to 120°C and the temperatures approach the upper limit at Çanakkale (Ezine, Bayramiç, Ayvacık), Balıkesir (Ayvalık), İzmir (Dikili, Buca), Aydın, Muğla (Datça), Denizli (Babadağ, Pamukkale, Honaz, Merkezefendi), Manisa-Kütahya (Demirci, Selendi, Simav, Şaphane, Pazarlar) and Eskişehir (İnönü, Seyitgazi, Çifteler, Han). The temperature distribution suggests that thermal conditions within the grabens are favorable for geothermal energy production. Actually, western Anatolia is ranked first in terms of geothermal energy production in Türkiye (Figure 5). The cities with well-known geothermal fields are as follows: Çanakkale (Tuzla), Balıkesir (Bigadiç, Hisaralan, Gönen), İzmir (Seferihisar, Balçova, Dikili, Aliağa, Çeşme), Aydın (Germencik, Salavatlı, Yımazköy-İmamköy), Denizli (Kızıldere, Gölemezli, Karahayıt, Pamukkale), Manisa (Salihli-Caferbeyli, Salihli-Kurşunlu, Alaşehir-Kavaklıdere, Turgutlu-Urganlı, Saraycık, Kula) and Kütahya (Simav, Gediz-Abide). In most of these areas, thermal energy production is made from the basement rocks, although in a few of them, it is produced from the neotectonic cover.

Because of the high success rate, western Anatolia has attracted considerable attention and therefore most of the geothermal energy investments have been made in this region. This attraction has caused excessive and damaging exploitations in the region, resulting in drops in reservoir pressures and the occurrence of great production problems (Şimşek, 1985, 2003; Özgür, 2002; Tüfekçi et al., 2010; Başel et al., 2013; Korkmaz et al., 2014; Erkan, 2015; Pazvantoğlu et al., 2021; Serpen et al., 2022).

5.4. North Anatolian Neotectonic Province

Examination of Figure 4 shows that temperature in this province at 1000 m depth changes in most places between 30°C and 50°C above the normal geo-gradient. However, in certain places such as Edirne, Silivri-Çerkezköy, Yalova, Sakarya, Düzce, Bolu, Karabük, and Kastamonu, the temperature reaches 60°C. These places, except Edirne and Silivri-Çerkezköy, are located in and around the NAFZ, indicating that the fault zone probably transferred the heat from the interior of the Earth to this depth. Edirne and Silivri-Çerkezköy areas are located in the Thrace Basin where volcanism was active in Eocene to Neogene time, including the neotectonic episode. This region is also under the effect of strike-slip tectonic activity during this episode. The deep strike-slip faults in these areas, such as Kırklareli, Lüleburgaz, Babaeski, and Ganos, might have formed pathways for the heat at depth to come to the surface.

North Anatolian Neotectonic Province doesn't show much volcanism and active tectonism, other than weak east-west shortening. Therefore its geothermal potential seems low. However, the Thrace Basin and the NAFZ may have high geothermal potential. The NAFZ, which is a plate boundary structure with a lithospheric scale, may serve as channels for heat and geothermal fluids from hot deeper levels of the crust to reach shallow depths and form rich geothermal sources. As a matter of fact, there are many surface manifestations like hot springs along this fault zone, including Yalova, Adapazarı, Düzce, Bolu, Amasya, Tokat, Erzincan, and Bingöl (Figure 4). The well-known geothermal fields along the fault zone comprise of Çekirge (Bursa), Armutlu (Yalova), Termal (Yalova), Akyazı (Sakarya), Kaplıca (Bolu), Mudurnu-Babas (Bolu), Seben-Kesenözü (Bolu), Hamamözü (Amasya), Gözlek (Amasya), Reşadiye (Tokat) and Kurşun-Çavundur (Çankırı). All these geothermal fields have developed in association with the NAFZ and its branches. Their reservoir and cover rocks are dominantly developed in the palaeotectonic terrains of the basement as they are situated on the different neotectonic provinces along the fault zone.

Most of the basins, which developed along the NAFZ, have high geothermal gradients but particularly those formed in the trans-tensional and pull-apart portions of the fault zone are favorable in terms of geothermal energy. Geothermal investigations in the NAFZ may be difficult, because of extremely complicated geology. This fault zone is superimposed on the İzmir-Ankara-Erzincan and Intra-Pontide sutures that represent the final closure of the Neo-Tethys Ocean. During the closure, palaeotectonic terrains to the north of the ocean thrusted over onto the terrains in the south together with the accretionary melange formed during the subduction. Accretionary melange also exits on the Pontides to the north of the sutures as retrocharriages. Of course, these tectonic events made the substratum geology of the North Anatolian Fault Zone too complicated. Despite all the complications, superimposed suture and the North Anatolian Fault Zone are the most convenient places for geothermal investigations as they may play an important role with their deep roots in the crust in conveyance of heat from the interior of the Earth to the shallow areas. There is no doubt that careful studies will lead to discoveries of rich geothermal resources (Mamontov et al., 2005; Yapmış et al., 2005; Maden, 2012; Başel et al., 2013; Görür and Elbek, 2013; Pasvanoğlu and Çelik, 2019; Temizel et al., 2021).

6. Results

This paper gives an up-to-date overview of the geothermal potential of Türkiye on the basis of the neotectonic episode in Türkiye. This episode is characterized by fluvio-lacustrine sediments and associated magmatism with a relatively high geothermal background induced by the continental collision between the Arabian and Eurasian plates. The most known geothermal systems in this country occur as hydrothermal systems, including both vapour-and liquid-dominated geothermal fields. However, the high thermal anomalies in the Central

Anatolian Ova Neotectonic Province indicate that the largest geothermal potential of Türkiye is perhaps the hot-dry rock (HDR) or enhanced geothermal systems (EGS) of this province. These systems today have significant technical and economic challenges. If they are overwhelmed in near future, Türkiye's commercial utilization of this resource will be immense by any measure. Therefore, exploration activities should be directed from the West Anatolian Extensional Province to the Central Anatolian Ova and the East Anatolian Contractional Provinces where HDR/EGS and hidden hydrothermal systems with no surface thermal manifestations may be common.

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