Contents list available at CBIORE journal website

International Journal of Renewable Energy Development

Journal homepage: https://ijred.cbiore.id

Research Article

Current status and potentials of enhanced geothermal system in the Eastern Pontide Orogenic Belt, Turkey

Mehmet Furkan Şener*

Department of Geography, Faculty of Arts and Sciences, İzmir Bakırçay University, Türkiye

Abstract. The radioactive decay of isotopes is one of the most important sources of heat in the Earth's interior. The main radiogenic elements in the crust are U, Th, and K in granitoids. Radiogenic granites are becoming increasingly important as they support the development of the renewable energy sector. This study provides an in-depth review of the development of Enhanced Geothermal Systems (EGS) technology. Many countries, such as France and the UK, have initiated and contributed to energy production using EGS technology. In addition, this study calculates the potential production capacity of radiogenic granites in the Eastern Pontide Oraganic Belt (EPOB) and assesses their significant contribution to the Turkish economy in line with the Sustainable Development Goals (SDGs). The total area of radiogenic granites within the EBOP is 7116.35 km^2 and these granites contain average concentrations of U 3.25 ppm, Th 16.44 ppm, and K 3.7%. The plutons studied can generally be classified as medium to low heat producing granitoids. Ayeser, Camiboğazı, and Ayder (3.36-6.98 μW/m^3), which are close to the average heat production value of the continental crust (5 μW/m^3), may be suitable areas for EGS. Currently, EBOP granites have the capacity to produce 61 x 109 kWh of electricity. In addition to electricity, heat from granites can be used for other applications such as space heating and greenhouse cultivation.

Keywords: Geothermal Energy, Radiogenic Granites, EGS, Eastern Pontide Orogenic Belt, Turkey.

Received: 28th Feb 2024; Revised: 24th March 2024; Accepted: 16th April 2024; Available online: 19th April 2024

1. Introduction

Although the world's energy resources are limited, the energy demand is increasing every day due to population growth and industrialisation. Rapid population growth and global social, economic, and industrial development are increasing energy demand (IEA, 2015). The use of fossil fuels is increasing day by day to meet this growing demand. The increasing use of fossil fuels has increasingly harmful effects on the global environment. Due to the problems associated with the use of fossil fuels, the need for alternative energy sources has increased since the late twentieth century. For a more livable world, renewable energy sources need to be expanded (Özkan *et al.,* 2011; Giellen *et al.,* 2019; Şener, 2019). In addition to being one of the renewable energy sources, geothermal energy is also a local and national resource. Therefore, expanding the use of renewable energy resources, such as geothermal energy, will contribute to the country's economy and also help to close the energy gap. The cost of renewable energy is significantly lower compared to other energy sources, ranging from 50% to 80%. Moreover, this percentage is steadily increasing with each passing day (Everett, 2007; Şener, 2018). Hydrothermal energy sources are typically confined to specific locations in volcanic regions, subduction zones, and deep continental rift valleys. EGS, on the other hand, is not site specific and can be implemented anywhere on the planet using the heat generated by granites (Tester *et al.,* 2006; Şener and Baba, 2019). Enhanced Geothermal Systems (EGS) refer to geothermal reservoirs that have been optimised for the economic use of low permeability conductive rocks. This optimisation is achieved by establishing fluid connectivity in initially low-permeability rocks through various techniques such as hydraulic, thermal, or chemical stimulation. Various countries have ventured into energy production using EGS technology. For instance, France has successfully implemented EGS for power generation, contributing 10 MWe of capacity. The United Downs Deep Geothermal Power Project in Cornwall, UK, has also made significant progress in this area, with a capacity of 3 MWe. Despite countries such as France (Baumgartner *et al.,* 1995), Australia (Chen, 2010), Germany (Breede *et al.,* 2013), and England (Brown, 2022) actively pursuing research and development in the field of EGS, Turkey has yet to implement EGS technology. As of 2022, Turkey's power generation capacity will reach 1682 MWe, and total installed direct heat use utilization amounted to 5113 MWt. These figures highlight Turkey's efforts to diversify its energy sources and move towards a more sustainable energy landscape. Turkey is heavily dependent on fossil fuels as its primary energy source, with an annual energy demand of approximately 384 billion kWh. However, Türkiye is located in an active tectonic zone due to its geological location. Although Turkey ranks fourth in the world and first in Europe in terms of geothermal energy production, it has many geothermal areas that have not yet been discovered but have potential (Jennejohn *et al.* 2012; Şener *et al.,* 2017). Turkey benefits from medium and high temperature geothermal fields due to its location within an active tectonic zone and a young volcanic belt. Among these locations, the

* Corresponding author
Email: furkan.sener@bakircay.edu.tr (M. F. Sener)

https://doi.org/10.61435/ijred.2024.60167
ISSN: 2252-4940/© 2024.The Author(s). Published by CBIORE

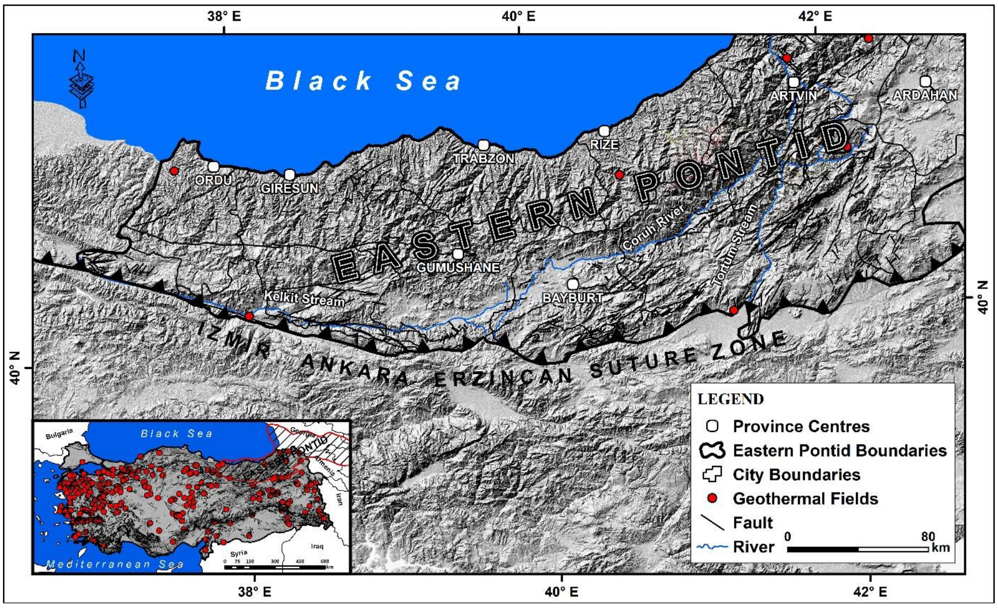

Fig 1. Tectonic units and structural zones of Turkey and location of the EPOB (modified from Okay and Tüysüz, 1999).

EPOB stands out as one of the regions with medium enthalpy geothermal resources (Karakaya *et al.,* 2007; Bayramoğlu, 2018; Gültekin *et al.*, 2019; Hatipoğlu Temizel *et al.*, 2019; Yücel, 2019; Hatipoğlu Temizel *et al.,* 2020; Vural and Gündoğdu, 2020; Karayel *et al.*, 2022; Şener *et al.,* 2023) and EGS potential (Şener *et al.*, 2022; Figure 1).

In addition to electricity generation, EGS technology offers significant advantages in terms of thermal applications such as suburban heating, greenhouse operation, drying processes, and even energy supply for the fishing industry. However, no studies have been conducted to investigate the EGS potential of the EPOB. This study represents the first research to evaluate the development of radiogenic granites in the EPOB region, focusing on their heat generation capacities and heat fluxes determined by their uranium, thorium, and potassium contents. It also compares the levelized cost of EGS with alternative energy sources and assesses the potential of EGS to facilitate future energy systems. In this study: (1). The heat generation capacity of granites in the EPOB was determined using published data on the uranium, thorium, and potassium contents of granites. (2). Estimates of the total power and heat production potential of these granites have been presented. (3). Technologies for extracting heat from the subsurface are presented, taking into account the specific characteristics of the granites in question. (4). The current potential of hydrothermal resources in the region for electricity and heat production has been examined.

2. Study Area

The study area, first defined by Ketin (1966) as the "Eastern Pontide Orogenic Belt (EPOB)", is located in

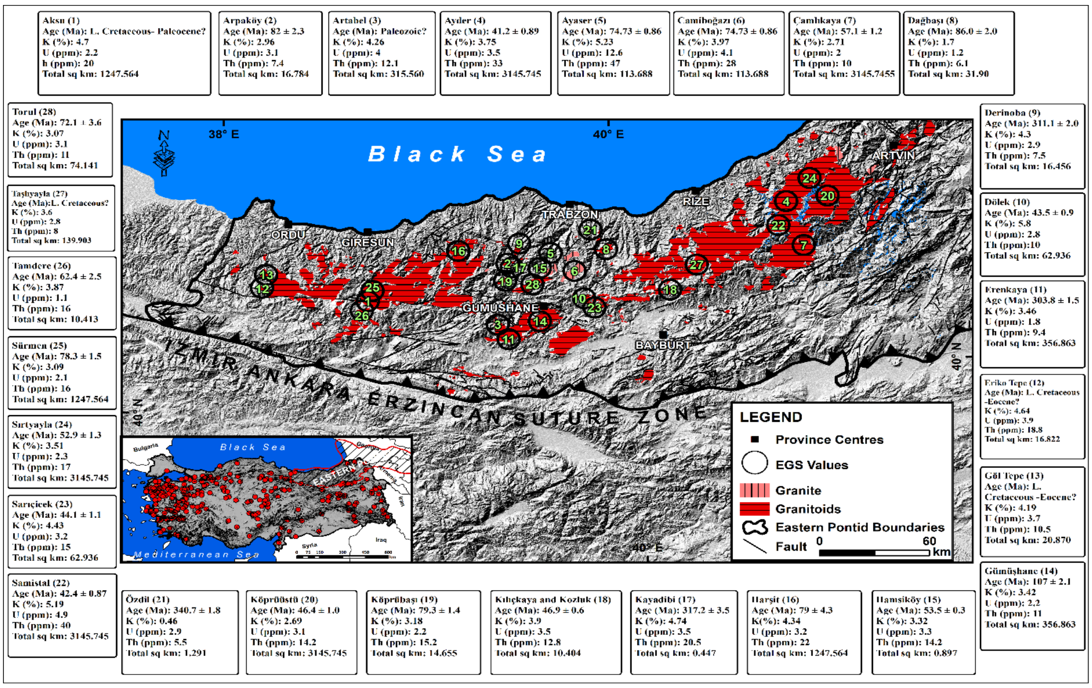

Fig 2. Granite intrusion of the EPOB, data sources is given in Table 1.

northeastern Turkey. The geodynamic evolution of the EPOB has different interpretations due to the lack of geochronological, geochemical, and structural data. The EPOB is 500 km long and 200 km wide (Figure 2). In general, there are three different views of the geodynamic evolution of the EPOB. The first view is that the EPOB was formed by the northward subduction of the oceanic lithosphere from the Palaeozoic to the Eocene (Adamia *et al.,* 1981; Tokel, 1981; Ustaömer and Robertson, 1996; Rice *et al.* 2006). The second view is that the EPOB was formed by the southward subduction of the oceanic lithosphere from the Paleozoic to the Middle Jurassic (Şengör and Yılmaz, 1981; Yılmaz *et al.,* 1997; Karslı *et al.,* 2012). The third view is that the EPOB was formed as a result of the southward subduction of the oceanic lithosphere from the Paleozoic to the Eocene (Bektaş *et al.,* 1999; Eyüboğlu *et al.,* 2011). The metamorphic units represent the oldest rocks of the EPOB, which is an important region within the Alpine-Himalayan belt (Eyüboğlu *et al.,* 2018; Eyüboğlu *et al.,* 2021). Furthermore, the region is characterised by the presence of different granite and granodiorite formations that can be attributed to different periods (Figure 2).

Significant lithological changes from north to south are observed in the EPOB in the Late Cretaceous. Volcanic rocks and granite intrusions formed as a result of intense magmatic activity in the northern belt are the dominant lithological features (Yılmaz and Boztuğ, 1996; Okay and Şahintürk, 1997; Karslı *et al.,* 2004; Boztuğ *et al.,* 2006; Kaygusuz *et al.,* 2010; Kaygusuz and Aydınçakır 2011; Aydınçakır and Şen, 2013; Aydınçakır, 2016), while the southern part is characterised by the Cenozoic sedimentary sequence (Yılmaz and Boztuğ, 1996; Şen *et al*., 1998; Boztuğ vd., 2004; Arslan and Aslan, 2006; Temizel *et al*., 2012; Arslan *et al.,* 2013; Aydınçakır and Şen, 2013; Aydınçakır, 2014; Aydınçakır, 2016; Temizel *et al.,* 2016). The EPOB is also one of the regions with EGS potential. Heat-generating granitoids in the EPOB are spread over an area of 7116.35 km^2. Although the whole area is considered as low to medium heat-producing granitoids in terms of radiogenic heat production values, Ayeser, Camiboğazı, and Ayder, located in an area of 259.64 km² with a value of 3.36-6.98 μW/m^3, are among the high heat-producing granitoids.

3. Method of study

This study aimed to analyse the potential for power generation, greenhouse heating, and balneotherapy through the application of EGS in EPOB. The advantage of this region is that these granites occur at shallow depths and with high heat flow regimes at shallow Curie Point Depth (CPD). The EPOB region covers a significant area of Late Cretaceous to Paleocene radiogenic granites with an area of 7116.35 km². (Boztuğ *et al.,* 2007; Kaygusuz *et al*., 2012a; Kaygusuz *et al*., 2021a). The aim is to evaluate the feasibility and benefits of using EGS technology for these specific applications in this field. In this context, K, U, and Th values of granite samples from 28 different locations within the EPOB, compiled from 28 different studies, were used (Table 1 and Figure 3). The U and Th are geochemically classified as trace elements, while K is considered the major element and is usually represented by the oxide K_2O. Radioactive heat production (A), heat flow (Q) values of granites from different sites were calculated from U (uranium), Th (thorium) and K (potassium) contents (Table 1).

The radiogenic heat production (A) rate is a physical property that defines the amount of heat that is liberated per unit time per unit volume of rock by the decay of unstable radioactive isotopes. The granites of the EPOB contain high concentrations of uranium (U), thorium (Th), and potassium (K), resulting in above average calorific values and significant heat production. The heat fluxes of these granites were determined using the equations proposed by Rybach (1976) and Cermak *et al.* (1982).

$$A(\mu W/m^3) = 10^{-2} * \rho * (9.52C_U + 2.56C_{Th} + 3.48C_K) \qquad (1)$$

Table 1
The ages and uranium, thorium, and potassium contents of the radioactive granites in the EPOB

Map Code	Name	K (%)	U (ppm)	Th (ppm)	Age	Reference
1	Aksu	4.7	2.2	20	Late Cretaceous–Paleocene ?	Yılmaz and Boztuğ, 1996
2	Arpaköy	2.96	3.1	7.4	82.0 ± 2.3 M	Kaygusuz *et al.,* 2021a
3	Artabel	4.26	4	12.1	Paleozoic?	Temizel *et al.,* 2018
4	Ayder	3.75	3.5	33	41.2 ± 0.89	Yılmaz Şahin *et al.,* 2004
5	Ayeser	5.23	12.6	47	74.73 ± 0.86	Kaygusuz *et al.,* 2012a
6	Camiboğazı	3.97	4.1	28	74.73 ± 0.86	Kaygusuz *et al.,* 2012a
7	Çamlıkaya	2.71	2	10	57.1 ± 1.2	Boztuğ *et al.,* 2007
8	Dağbaşı	1.7	1.2	6.1	86.0 ± 2.0	Kaygusuz and Aydınçakır, 2011
9	Derinoba	4.3	2.9	7.5	311.1 ± 2.0	Kaygusuz *et al.,* 2012b
10	Dölek	5.08	2.8	10	43.5 ± 0.9	Karslı *et al.,* 2007
11	Erenkaya	3.46	1.8	9.4	303.8±1.5	Kaygusuz *et al.,* 2021b
12	Eriko Tepe	4.64	3.9	18.8	Late Cretaceous -Eocene?	Temizel *et al.,* 2018
13	Göl Tepe	4.19	3.7	10.5	Late Cretaceous -Eocene?	Temizel *et al.,* 2018
14	Gümüşhane	3.42	2.2	11	107± 2.1	Topuz *et al.,* 2010
15	Hamsiköy	3.32	3.3	14.2	53.5 ± 0.3	Karslı *et al.,* 2011
16	Harşit	4.34	3.2	22	79 ± 4.3	Karslı *et al.,* 2010
17	Kayadibi	4.74	3.5	20.5	317.2 ± 3.5	Kaygusuz *et al.,* 2012b
18	Kılıçkaya and Kozluk	3.9	3.5	12.8	46.9 ± 0.6	Kaygusuz and Aydınçakır, 2011
19	Köprübaşı	3.18	2.2	15.2	79.3 ± 1.4	Kaygusuz and Şen, 2011
20	Köprüüstü	2.69	3.1	14.2	46.4 ± 1.0	Boztuğ *et al.,* 2007
21	Özdil	0.46	2.9	5.5	340.7 ± 1.8 Ma	Kaygusuz *et al.,* 2012b
22	Samistal	5.19	4.9	40	42.4 ± 0.87	Yılmaz Şahin *et al.,* 2004
23	Sarıçiçek	4.43	3.2	15	44.1 ± 1.1	Karslı *et al.,* 2007
24	Sırtyayla	3.51	2.3	17	52.9 ± 1.3	Boztuğ *et al.,* 2007
25	Sürmen	3.09	2.1	16	78.3 ± 1.5	Yılmaz and Boztuğ, 1996
26	Tamdere	3.87	1.1	16	62.4 ± 2.5	Yılmaz and Boztuğ, 1996
27	Taşlıyayla	3.06	2.8	8	Late Cretaceous?	Kaygusuz *et al.,* 2021b
28	Torul	3.07	3.1	11	72.1 ± 3.6	Kaygusuz and Sahin, 2016

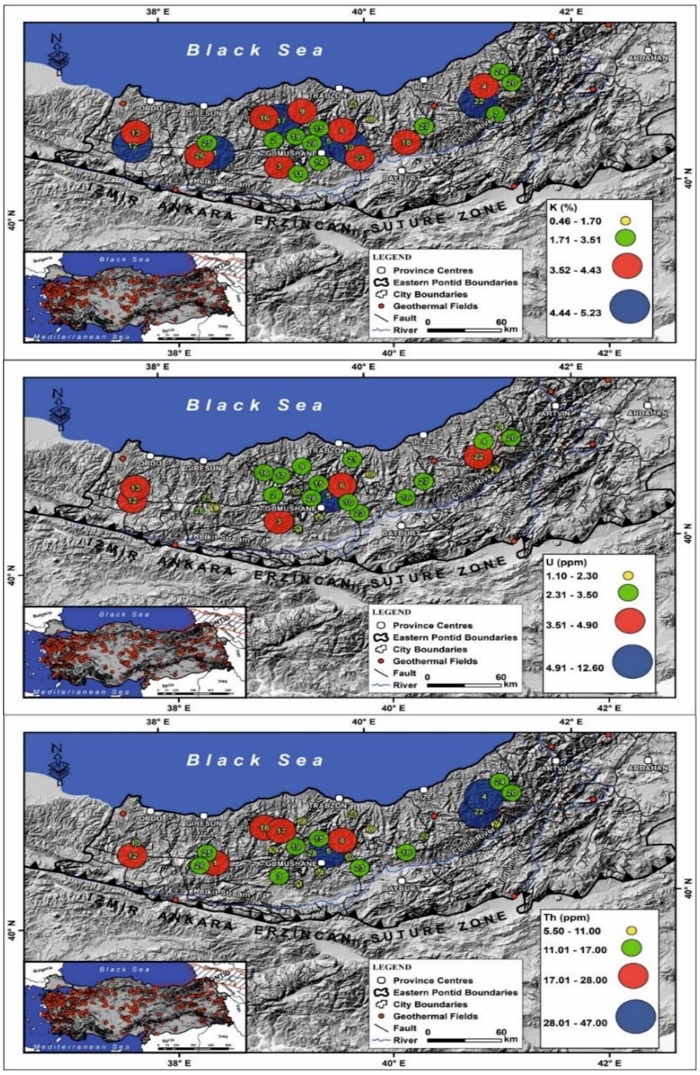

Fig 3. Spatial distribution of K (%), U (ppm), and Th (ppm) statistics in the EPOB (location numbers and element values are given in Table 1)

where, A is the heat production of the granite, $\rho(g/cm^3)$ is the density of the granite (the average density for granitoid is 2.7 g/cm^3; Cooper *et al.*, 2010; Chandrasekharam *et al.*, 2022), C_U is uranium (ppm), C_{Th} is thorium (ppm), and C_K is potassium (%)

Deep geothermal investigations based on heat flux data are the main method of exploring the deep thermal state of the lithosphere. Heat flux represents the heat that is transferred by conduction per unit area per unit of time from the Earth's interior to the surface and then radiated into space. Under one-dimensional steady state conditions, heat flow is the product of the thermal conductivity of the rock and the vertical geothermal gradient. Surface heat flux values are calculated using the Lachenbruch (1979) equation:

$$Q = Q_0 + D * A \quad (2)$$

where Q is the surface heat flow, Q_0 is an initial value of the heat flow independent of the specific decay of the radioactive element at a certain time, D is the thickness of rock over which the distribution of radioactive elements is almost homogeneous, A is the radioactive heat production

The study also examined the economic benefits of EGS as a primary energy source, taking into account the progress and results of ongoing EGS projects around the world. In addition, the study sought to provide alternative projections for policymakers, investors, and energy stakeholders by examining the economic feasibility, cost effectiveness, and potential financial benefits of EGS technologies. In addition, the study sought to highlight Turkey's potential to use both EGS and hydrothermal energy sources as strategic tools to reduce CO_2 emissions, combat global climate change, and promote sustainable development. The development of EGS and hydrothermal energy sources can ensure long-term energy security, create jobs, and promote sustainable economic growth in the country. Overall, this study highlights the potential of EGS and hydrothermal energy sources as critical elements in achieving Turkey's sustainable energy transition, environmental management, and climate change mitigation goals.

4. Results

4.1 Radiogenic Heat Production of Granites

Statistical studies show that the thermal contributions of the Earth's heat-generating elements U and Th are currently relatively similar, about 40% each, while the thermal contribution of K is relatively small (~20%) (Arevalo et al., 2009). Figure 4 shows the variation of radiogenic elements in the cores of different areas and their proportions. It can be seen that the volumetric heat production of the rocks increases with increasing U, Th, and K concentrations.

The U and Th have a significant positive relationship with heat production (Figure 5a, Figure 5b), while the correlation between K concentration and heat production shows significant

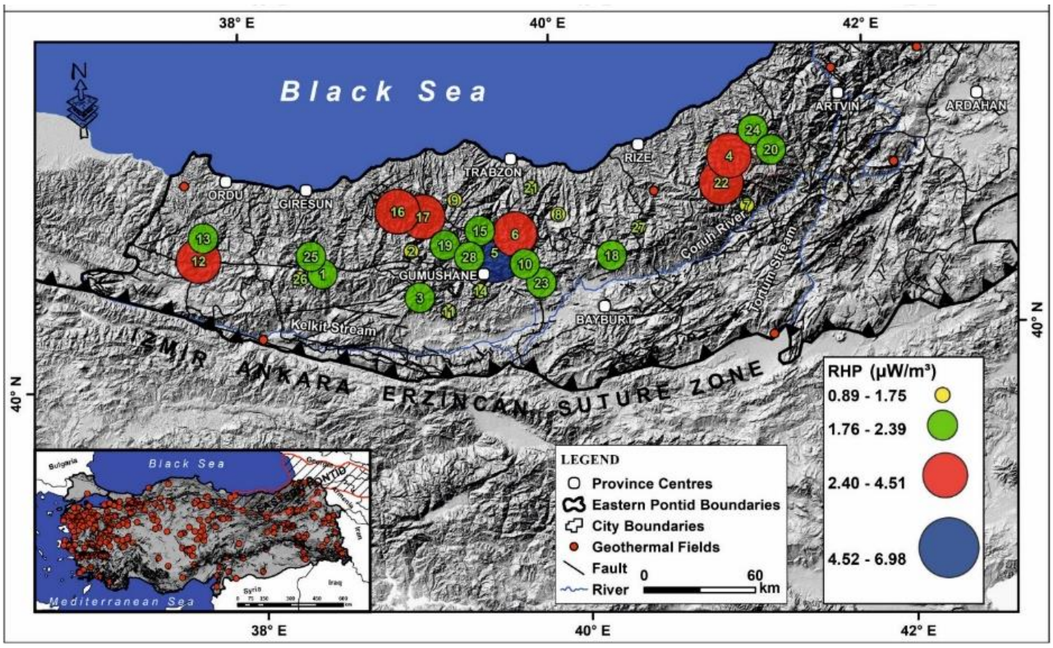

Fig 4. Spatial distribution of A (µW/m³) statistics in the EPOB (location numbers and element values are given in Table 1 and Figure 2.)

scatter (Figure 5c). This may indicate that the proportion of K in the total heat production is relatively small in terms of heat contribution. The radiogenic elements found in the study area are shown in the U-Th-K triangle (Figure 5d), indicating that U and Th are the main components of radiogenic heat. The EPOB data are relatively concentrated, with average thermal contributions of Th and U between 23% and 36%. In contrast, the contribution of K is relatively low, averaging less than 13%, which is closer to the global average. This indicates that the radiogenic contribution of U in the EPOB is relatively high, which is consistent with the results obtained by Arslan et al., (2023). Statistical results show that the Th/U ratios of the granites in the study area vary between 1.9 and 14.554, with an average value of 5.45, which is consistent with the average Th/U ratio of 4.2 in the upper crust (Van Schmus, 2013).

4.2 Heat flow

The average crustal thickness of the EPOB region varies between 14 km and 27 km, with an average thickness of about 20.5 km (Maden *et al.,* 2009). In recent years, geophysical investigations have been carried out to reveal the crustal structures and heat flux properties that indicate the geothermal potential of EPOB (Bektaş *et al.,* 2007, Maden *et al.,* 2009, Pamuk, 2019, Elmas, 2021). In addition, surface heat flux density values vary between 66.5 and 104 mW/m² (Maden *et al.*, 2009). The very high mantle heat flux density, which reaches 48 mW/m² in the region, is attributed to lithospheric mantle melting caused by asthenospheric uplift (Maden, 2012). Pamuk (2019) also suggested that the heat flux values in the southern part of the EPOB are between 75 and 95 mW m². Considering the estimated natural heat flux from the mantle of 85 mW/m² in

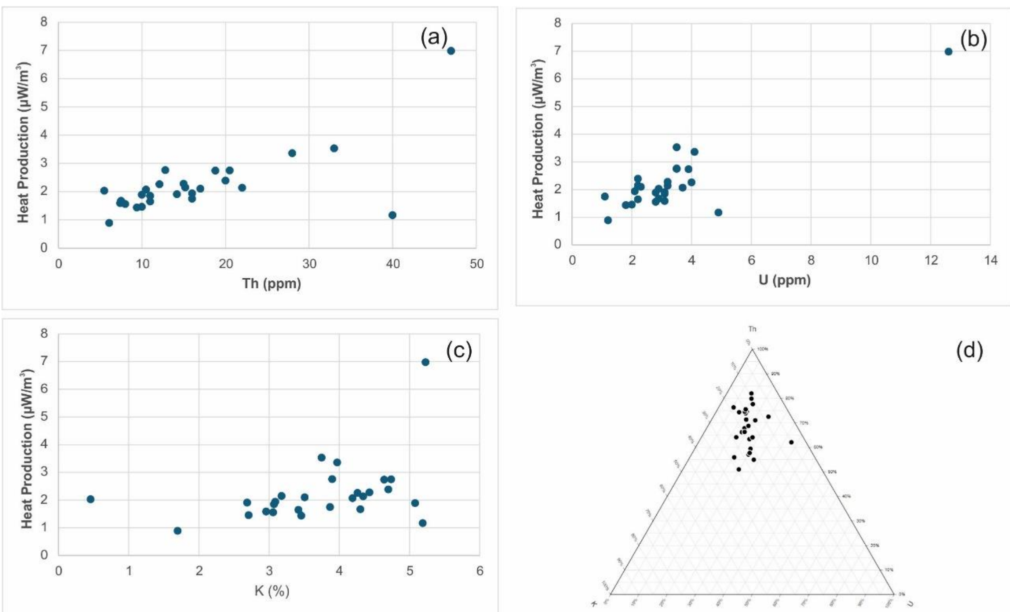

Fig 5. Radiogenic heat production versus concentrations of radiogenic (a) Th, (b) U, and (c) K ratios and (d) Ternary scatter plot of heat production of all of the samples gathered from the EPOB

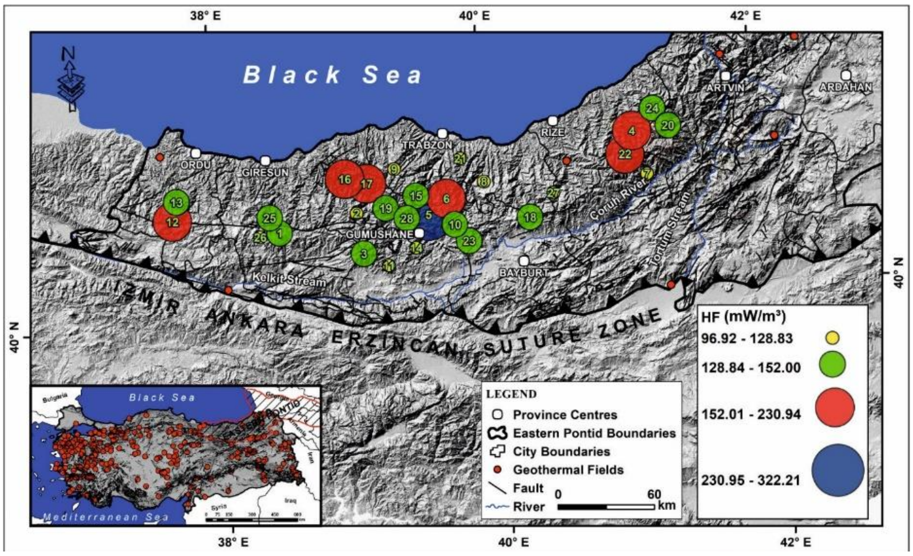

Fig 6. Spatial distribution of Q (mW/m³) statistics in the EPOB (location numbers and element values are given in Table 1 and Figure 2.)

the EPOB region and the crustal thickness of 20.5 km, the estimated heat flux in this region is extremely high, as shown in Table 2. According to Turcotte and Schubert, 2002, the radiogenic heat production of granitoids contributes 65 mW/m² to the continental surface heat flux, of which 40% is due to radiogenic heat production in the crust and 60% in the mantle. For this reason, radiogenic heat from granitic plutons in the EPOB may play an important role in the crustal surface heat flux characteristics of the region. Therefore, the Paleogene Ayeser, Ayder, and Camiboğazı granite intrusions have the highest A (μW/m³) 6.98, 3.53, 3.36, and Q (mW/m³) 322.2, 194.7, 188.4 values, respectively, while the granodiorite intrusions in the area have 0.89-2.76 A (μW/m³) and 96.9-166.2 Q (mW/m³) values (Table 2 and Figure 6).

4.3 Hydrogeological settings

The lithological units in the geothermal areas of the EPOB are classified according to their hydrogeological characteristics. The main granitoids (including granite, granodiorite, and tonalite) are widely exposed and show permeability due to fracture systems, within the geothermal areas of the study area. Intensive weathering processes are evident in the granodiorites, which consist mainly of quartz, plagioclase, alkali feldspar, hornblende, biotite, and muscovite. The weathering products include clay minerals, chlorite, sericite, and epidote minerals (Gürsel, 1991). In areas, the well-developed fracture system in the major granitoid rocks facilitates the migration of meteoric water from deeper regions to the surface. The heated water by deep circulation is stored in fault zones and fractures of the main

Table 2
The radioactive heat production A (μW/m³) and heat flow Q (mW/m³) values of certain granitic intrusive in the EPOB

Map_Code	Name	A (μW/m³)	Q (mW/m³)	Square km
1	Aksu	2.39	152.0	1247.6
2	Arpaköy	1.59	122.0	16.8
3	Artabel	2.26	148.0	315.6
4	Ayder	3.53	194.7	3145.7
5	Ayeser	6.98	322.2	113.7
6	Camiboğazı	3.36	188.4	113.7
7	Çamlıkaya	1.46	118.0	3145.7
8	Dağbaşı	0.89	96.9	31.9
9	Derinoba	1.67	125.7	16.5
10	Dölek	1.89	133.9	62.9
11	Erenkaya	1.44	117.2	356.9
12	Eriko Tepe	2.74	165.3	16.8
13	Göl Tepe	2.07	140.6	20.9
14	Gümüşhane	1.65	124.9	356.9
15	Hamsiköy	2.14	143.24	0.90
16	Harşit	2.14	143.2	1247.6
17	Kayadibi	2.75	165.8	0.4
18	Kılıçkaya and Kozluk	2.76	166.2	10.4
19	Köprübaşı	2.15	143.6	14.7
20	Köprüüstü	1.91	134.9	3145.7
21	Özdil	2.03	139.2	1.3
22	Samistal	1.17	107.3	3145.7
23	Sarıçiçek	2.28	148.2	62.9
24	Sırtyayla	2.10	141.6	3145.7
25	Sürmen	1.94	135.6	1247.6
26	Tamdere	1.75	128.8	10.4
27	Taşlıyayla	1.56	121.7	139.9
28	Torul	1.85	132.3	74.1

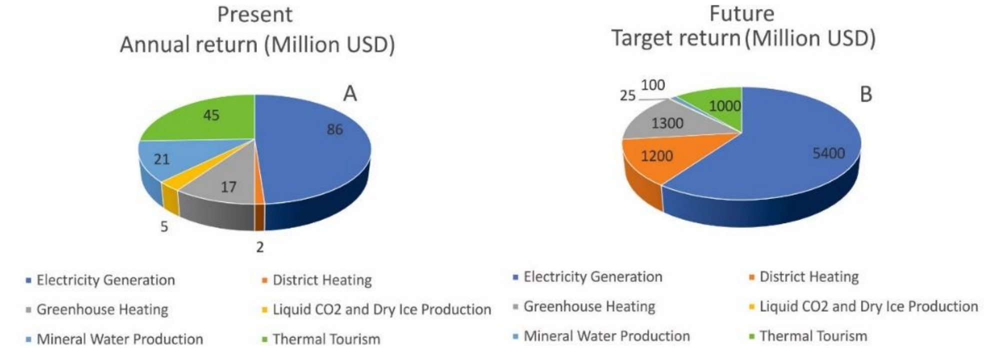

Fig 7. The annual contribution (a) and probable target to be reached in the future (b) of geothermal energy to the Turkish economy in terms of electricity and direct use (USD/year).

granitoid rocks. It then rises to the surface under hydrostatic pressure. The debris rocks on granitoid rocks act as caprock for geothermal systems. In addition, geothermal water temperatures in the geothermal areas of the EPOB generally vary between 38 and 60°C. The water types generally consist of $Na\text{-}Ca\text{-}SO_4$, $Na\text{-}Ca\text{-}HCO_3$, and $Na\text{-}Ca\text{-}HCO_3\text{-}SO_4$, and the pH values vary between 7 and 9.3 (Hatipoğlu Temizel *et al.*, 2019).

4.4 Contribution of Geothermal Energy to the National Economy

One of the main economic benefits associated with geothermal energy is its potential to minimize dependence on imported fuels. Consequently, directing domestic investment towards the development of geothermal energy resources can effectively reduce the trade deficit while maintaining a robust level of *gross domestic product* (GDP). In addition to its environmental and energy security benefits, geothermal heating has a cost advantage of at least 60% over fossil fuels. In many locations, the cost of geothermal heating is currently around 70% less than the cost of natural gas (based on local domestic tariffs). This significant price difference becomes even more significant when considering the use of natural gas for domestic heating. This illustrates the significant contribution of geothermal energy to the country's economy. Compared to the current cost of natural gas, which is approximately 13.32 TL/m^3 (based on the BOTAŞ natural gas wholesale price tariff for July 2023), geothermal energy offers a significantly more economical option, amounting to approximately one eighth of the cost. This significant cost advantage benefits both the state and the general public. The specific details of the economic contribution of geothermal energy in terms of electricity generation and direct use can be found in Figure 7. Based on the calculations, the direct contribution of geothermal applications to the economy totals 3,918,411,000 USD (excluding factors such as employment, natural gas savings, and CO_2 emission reductions). Additionally, taking into account an estimated 5% attributed to unknown and unrecorded factors, the direct contribution of geothermal applications to the economy can be approximated at around 4.1 billion USD per year (Şener *et al,* 2022).

Given the economic benefits, it is recommended that priority be given to the development of regions in Turkey with significant geothermal potential, using technologies such as EGS. It should be noted that EGS is currently under development and the estimated cost of electricity generation may vary depending on factors such as the heat flow and heat generation capacity of the granites present in the respective areas. The Curie Point Temperature of 14.3 ± 0.7 – 27.9 ± 1.4 km (Maden *et al*., 2009) and the high heat flux of granites of 2.83 ± 1.39 μWm^{-3} (Maden and Akaryalı, 2015) are an additional advantage for the EPOB. Although the cost of energy produced from fossil fuels appears to be lower than that of renewable energy sources, it is important to consider the overall cost implications (costs incurred due to import and export deficits and environmental impacts). In addition, according to the results of the Turkish National Energy Plan, electricity consumption is expected to be 380.2 TWh in 2025, 455.3 TWh in 2030, and 510.5 TWh in 2035. Electricity generation in 2022: coal: 34.6%, natural gas: 22.2%, hydropower: 20.6%, wind: 10.8%, solar: 4.7%, geothermal: 4.7%: 4.7%, geothermal: 3.3% and other sources: % 3.7. The distribution of Turkey's installed capacity, which reached 104,496 MW at the end of April 2023, by resource is as follows 30.2% hydro, 24.3% natural gas, 20.9% coal, 11% wind, 9.5% solar, % 1.6 geothermal and 2.5% other sources. In addition, the number of power plants in Turkey reached 11,941 (including unlicensed power plants) at the end of April 2023. The distribution of power plants by resource is as follows: 751 hydro, 67 coal, 361 wind, 63 geothermal, 345 natural gas, 9,863 solar, and 491 other power plants (Turkey National Energy Plan, 2022).

5. Discussion

Turkey is at the forefront of implementing laudable efforts in the field of renewable energy, paying special attention to the effective use of geothermal resources, facilitating sustainable development, and accelerating economic growth. One of the effective uses of geothermal resources is EGS studies, and the effective implementation of these EGS studies in countries such as France and Australia serve as a promising indicator for the prospective integration of granites with advanced thermal capacity as an important component in the global energy supply paradigm. These advances highlight the potential of EGS technology to harness the abundant thermal energy latent in geological formations, thereby signaling a feasible and sustainable solution to meet the ever-increasing global energy demand (Vigneresse *et al.,* 1987; Chen, 2010, Omenda *et al.,* 2012; Zhang *et al.,* 2014; Arslan *et al.,* 2023). EGS is a conceptual approach in which a series of fractures are deliberately created in a high-temperature (radiogenic) granite at a depth of 2 to 5 km. The main purpose of this process is to increase the porosity and permeability of the granite formation. Fluids such as water or supercritical carbon dioxide are then injected into these fractures to facilitate the release of the heat trapped in the rock, making it available for a variety of applications such as power generation, domestic heating, and greenhouse farming. A single well in such an EGS system has the potential to produce approximately 3 to 4 megawatts of electricity (MWe) and 20 to 40 megawatts of heat (MWt) (Cooper *et al.,* 2010; Breede *et al.,* 2013; Koelbel and Genter, 2017; Pan *et al.,* 2019; Chandrasekharam and Baba, 2021; Chandrasekharam *et al.*, 2022; Baba and Chandrasekharam, 2022). In the proposed system, the heat produced by the EGS is transferred to a low boiling point fluid via a heat exchanger. This fluid operates at high pressure. The resulting pressurised steam is fed to a turbine which drives the generator. This arrangement typically uses Organic Rankine Cycle (ORC) technology to convert thermal energy into electricity. This process of extracting energy from granite is characterized by its cleanliness and absence of emissions. In addition, as the heat source comes from the ground, it provides a continuous and sustainable energy supply. This heat can be used directly for applications such as space heating and greenhouse cultivation, providing additional benefits beyond electricity production (Baba and Chandrasekharam, 2022). The Anatolian Plate, characterized by extensive granite intrusions, is an ideal region for the application of EGS technology. Radiogenic granites found in this region derive their heat from radioactive elements such as uranium (U), thorium (Th), and potassium (K). The heat production capacity of normal granites is about (~5μW/m3) (Zhang *et al*., 2022). The heat production of radiogenic granites in the Anatolian Plate varies between 5.36 and 13.10 μW/m^3, providing significant potential for geothermal energy utilisation through EGS technologies (Şener *et al.,* 2023). Radiogenic granite areas in the EPOB generally have average heat production capacity values (range 0.89 to 4.51 μW/m^3), while the Late Cretaceous Ayeser granites have a higher heat production capacity than other areas (6.98 μW/m^3). The EGS project conducted in the Cooper Basin has shown that the development of 1 km^3 of geothermal resources has the capacity to generate an estimated 79x10^6 kWh of electricity over 30 years (Chen, 2010). This finding suggests that long-term and sustainable energy production may be possible through the use of EGS technology in geothermal energy production (Cooper *et al.,* 2010). Covering an area of approximately 7116.35 km², the EPOB is characterised by the presence of highly radiogenic granite and granodiorite formations. In addition, the granites and granodiorites in this region are subject to compressive stress in the W-E direction of the Izmir-Ankara-Erzincan Suture Zone (IAESZ). The unique combination of radiogenic granite deposits and simultaneous compressive stress makes the EPOB region a suitable environment for the effective application of EGS technology. Some of the granitic plutons within the EPOB have low radiogenic heat production values (<3 μW/m^3), so these plutons are unlikely to provide a sufficient geothermal gradient for direct economic use of heat. However, the Camiboğazi, Ayder, and Ayeser granite plutons can be considered as medium (3-5 μW/m^3) and high (>5 μW/m^3) radiogenic granitoids. The area of radiogenic granitoid that can produce heat is 259.64 km², and the electricity that a 1 km thick slab with an area of 259.64 km² at a depth of 3 km can produce (knowing that 1 km^3 can produce about 79 x 10^6 kWh of electricity) is about 61 x 10^9 kWh of electricity.

.

6. Conclusion

Turkey is located in an active tectonic region characterised by a geologically young volcanic belt. In particular, EPOB is located in the northeastern part of this dynamic tectonic region. The radiogenic granites discovered at EPOB have significant potential for applications in various fields such as thermal suburbanization, greenhouses, desiccation, fisheries, and other related fields suitable for medium enthalpy use. Some of the granitic plutons within the EPOB have low radiogenic heat production values (<3 μW/m^3), so these plutons are unlikely to provide a sufficient geothermal gradient for direct economic use of heat. However, the Camiboğazi, Ayder, and Ayeser granite plutons can be considered as medium (3-5 μW/m^3) and high (>5 μW/m^3) radiogenic granitoids. The area of radiogenic granitoid that can produce heat is 259.64 km², and the electricity that a 1 km thick slab with an area of 259.64 km² at a depth of 3 km can produce (knowing that 1 km^3 can produce about 79 x 10^6 kWh of electricity) is about 61 x 10^9 kWh of electricity. This shows that the electricity that can be produced is equivalent to the electricity consumption of approximately 2.5 million households in the EPOB region for 117 months and will also pay for itself in about 5 years. When compared to other energy sources (fossil fuels), the electricity produced will contribute to both the national economy and employment. For example, the average gas consumption per household in Turkey is approximately 1000 m^3, which translates into an annual expenditure of approximately 20,280 TL (equivalent to approximately 624 USD) for the residential gas consumer. However, this expenditure can be significantly reduced by replacing gas consumption with geothermal heat from both hydrothermal and EGS sources. Detailed geophysical surveys such as the above, magnetotelluric (MT), and deep resistivity measurements may be useful in assessing radiogenic heat production. It is also recommended that consideration be given to drilling an exploratory well to monitor the thermal gradient and to obtain core samples of the granite to allow complementary petrophysical investigations. EGS power generation has the potential to have a significant impact on the country's economy. The implementation of resilient infrastructure and a comprehensive renewable energy policy is essential as a critical component of future strategies to reduce dependence on energy imports. In addition, the use of energy from EGS can contribute to increasing agricultural exports by increasing greenhouse production. Finally, geothermal research needs strong support from both local and central governments and stakeholders for the successful implementation of EGS. Inadequate public information and, in some cases, prejudice on the part of local people are the main obstacles to the development and implementation of new geothermal applications. Therefore, to increase public acceptance, it is necessary to raise public awareness that geothermal energy is a new, renewable, and environmentally friendly energy source.

References

Adamia, S.A., Chkhotua, T., Kekelia, M., Lordkipanidze, M., Shavishvili, I., Zakariadze, G. (1981). Tectonics of the Caucasus and adjoining regions: implications for the evolution of the Tethys ocean. *Journal of Structural Geology*, 3(4), 437-447. https://doi.org/10.1016/0191-8141(81)90043-2

Arevalo Jr, R., McDonough, W.F., Luong, M. (2009). The K/U ratio of the silicate Earth: Insights into mantle composition, structure, and thermal evolution. *Earth and Planetary Science Letters*, *278*(3-4), 361-369. https://doi.org/10.1016/j.epsl.2008.12.023

Arslan, M., Aslan, Z. (2006). Mineralogy, petrography, and whole-rock geochemistry of the Cenozoic granitic intrusions in the Eastern Pontides (Turkey). *Journal of Asian Earth Sciences*, 27, 177-193. https://doi.org/10.1016/j.jseaes.2005.03.002

Arslan, M., Temizel, I., Abdioğlu, E., Kolaylı, H., Yücel, C., Boztuğ, D., Şen, C. (2013). 40 Ar–39 Ar dating, whole-rock, and Sr–Nd–Pb isotope geochemistry of post-collisional Eocene volcanic rocks in the southern part of the Eastern Pontides (NE Turkey): implications for magma evolution in extension-induced origin. *Contributions to Mineralogy and Petrology*, *166*, 113-142. https://doi.org/10.1007/s00410-013-0868-3

Arslan, M., Temizel, İ., Temizel, E. H. (2023). Temporal and spatial radiogenic heat production rate of granitic plutons from the Eastern Pontides Orogenic Belt, NE Turkey: Constraints for the geothermal resources. *Journal of Asian Earth Sciences: X*, *10*, 100162. https://doi.org/10.1016/j.jaesx.2023.100162.

Aydınçakır, E., Şen, C. (2013). Petrogenesis of the post-collisional volcanic rocks from the Borçka (Artvin) area: implications for the evolution of the Eocene magmatism in the Eastern Pontides (NE

Turkey). Lithos, 172, 98-117. https://doi.org/10.1016/j.lithos.2013.04.007

Aydınçakırr, E. (2014). The Petrogenesis of Early Eocene Non-adakitic 108 Volcanism in NE Turkey: Constraints on the Geodynamic Implications, Lithos, 208/209, 361-377. https://doi.org/10.1016/j.lithos.2014.08.019

Aydınçakır, E. (2016). Subduction-related Late Cretaceous high-K volcanism in the Central Pontides orogenic belt: Constraints on geodynamic implications. *Geodinamica Acta,* 28(4), 379-411. https://doi.org/10.1080/09853111.2016.1208526

Baba, A., Chandrasekharam, D. (2022). Geothermal resources for sustainable development: A case study. *International Journal of Energy Resources* 46, 20501–20518. https://doi.org/10.1002/er.7778

Baumgartner, J., Lyman, M.P., and Andre, G. 1995. Drilling of hot and fractured granite at Soultz sous Forets (France). Proceedings, World Geothermal Congress, 1995, Florence, Italy, Vol 4.

Bayramoğlu, T. (2018). Yenilenebilir Enerji Potansiyeli ve Etkileri: Bayburt Örneği. İşletme Ekonomi ve Yönetim Araştırmaları Dergisi, 1(1), 1-16.

Bektaş, O., Şen, C., Atici, Y., Köprübaşi, N. (1999). Migration of the Upper Cretaceous subduction-related volcanism towards the back-arc basin of the eastern Pontide magmatic arc (NE Turkey). *Geological Journal*, 34(1-2), 95-106. https://doi.org/10.1002/(SICI)1099-1034(199901/06)34:1/2<95::AID-GJ816>3.0.CO;2

Bektaş, Ö., Ravat, D., Büyüksaraç, A., Bilim, F., Ateş, A. (2007). Regional geothermal characterisation of East Anatolia from aeromagnetic, heat flow and gravity data. *Pure and Applied Geophysics,* 164, 975-998. https://doi.org/10.1007/s00024-007-0196-5

Boztuğ, D., Jonckheere, R.c., Wagner, G.A., Yeğingil, Z. (2004). Slow Senonian and fast Paleocene-Early Eocene uplift of the granitoids in the Central Eastern Pontides, Turkey: apatite fission-track results. *Tectonophysics,* 382, 213-228. https://doi.org/10.1016/j.tecto.2004.01.001

Boztuğ, D., Erçin, A.İ., Kuruçelik, M.K., Göç, D., Kömür, İ., İskenderoğlu, A. (2006). Geochemical characteristics of the composite Kaçkar batholith generated in a Neo-Tethyan convergence system, Eastern Pontides, Turkey. *Journal of Asian Earth Sciences*, 27(3), 286-302. https://doi.org/10.1016/j.jseaes.2005.03.008

Boztuğ, D., Jonckheere, R., Wagner, G.A., Erçin, A.I. and Yeğingil, Z. (2007). Titanite and zircon fission-track dating resolve successive igneous episodes in the formation of the composite Kaçkar batholith in the Turkish Eastern Pontides. *International Journal of Earth Sciences*, *96*, 875-886. https://doi.org/10.1007/s00531-006-0140-4

Breede K, Dzebisashvili K, Liu X, Falcone G. (2013). A systematic review of enhanced (or engineered) geothermal systems: past, present and future. *Geotherm Energy*. (1): 4. https://doi.org/10.1186/2195-9706-1-4

Brown, C. S. (2022). Regional geothermal resource assessment of hot dry rocks in Northern England using 3D geological and thermal models. *Geothermics*, *105*, 102503. https://doi.org/10.1016/j.geothermics.2022.102503

Chandrasekharam, D., Baba, A. (2021). High heat generating granites of Kestanbol: future enhanced geothermal system (EGS) province in western Anatolia. *Turkish Journal of Earth Sciences*, *30*(9), 1032-1044. https://doi.org/10.3906/yer-2106-16

Chandrasekharam, D., Baba, A., Ayzit, T., & Singh, H. K. (2022). Geothermal potential of granites: case study-Kaymaz and Sivrihisar (Eskisehir region) Western Anatolia. *Renewable Energy*, *196*, 870-882. https://doi.org/10.1016/j.renene.2022.07.035

Cermak, V., Huckenholz, H.G., Rybach, L., Schmid, R. (1982). Radioactive heat generation in rocks. In: K Hellwege, ed. Landolt-Bornstein Numerical Data and Functional Relationships in Science and Technology. Springer, Berlin, Heidelberg, New York: New Series, Group V. Geophysics and Space Research; 1982: 433-481.

Chen, D. (2010). Concepts of a basic EGS model for the Cooper Basin, Australia. In Proceedings World Geothermal Congress 2010 Bali, Indonesia, 25-29 April 2010

Cooper, G.T., Beardsmore, G.R., Waining, B.S., Pollington, N., Driscoll, J.P. (2010). The relative costs of engineered geothermal system exploration and development in Australia. In *Proceedings of the World Geothermal Congress*.

Correia, A., Ramalho, E.C. (1999). One-dimensional thermal models constrained by seismic velocities and surface radiogenic heat production for two main geotectonic units in southern Portugal. *Tectonophysics*, *306*(3-4), 261-268. https://doi.org/10.1016/S0040-1951(99)00059-1

Elmas, A. (2021). Tectonic and crustal structure of the Eastern Pontides using Bouguer gravity data. *Acta Geophysica*, 69(5), 1637-1650. https://doi.org/10.1007/s11600-021-00640-3

Everett, B. (2007). Saving energy-how to cut energy wastage, D. Elliott (Ed.), Sustainable Energy, Opportunities and Limitations, Palgrave Macmillan, 108-134.

Eyüboğlu, Y., Chung, S.L., Santosh, M., Dudas, F.O., Akaryalı, E. (2011). The transition from shoshonitic to adakitic magmatism in the Eastern Pontides, NE Turkey: implications for slab window melting. *Gondwana Research*, 19(2), 413-429. https://doi.org/10.1016/j.gr.2010.07.006

Eyüboğlu, Y., Dudas, F.O., Chatterjee, N., Santosh, M., Billor, M.Z., Yuva, S. (2018). Petrology, geochronology and tectonic setting of early Triassic alkaline metagabbros from the Eastern Pontide Orogenic Belt (NE Turkey): Implications for the geodynamic evolution of Gondwana's early Mesozoic northern margin. *Tectonics,* 37(9), 3174-3206. https://doi.org/10.1029/2017TC004837

Eyüboğlu, Y., Dudás, F.Ö., Zhu, D.C., Santosh, M., Liu, Z., Chatterjee, N., Yi, K. (2021). Late Cretaceous alkaline magmas of the Eastern Pontides Orogenic Belt (NE Turkey): A review with new geological, geochemical and geochronological data. *Gondwana Research*, 97, 204-239. https://doi.org/10.1016/j.gr.2021.05.009

Gürsel, F. 1991. Ayder (Çamlıhemşin-Rize) ve Çevresinin Jeotermal Enerji Yönünden İncelenmesi, (MSc Thesis), Karadeniz Teknik Üniversitesi Fen Bilimleri Enstitüsü

Giellen, D., Boshell, F., Saygin, D., Bazilian, M.D., Wagner, N., Gorini, R. (2019). The role of renewable energy in the global energy transformation. *Energy Strateg. Rev*. 24, 38–50. https://doi.org/10.1016/j.esr.2019.01.006

Gültekin, F., Hatipoğlu Temizel, E., Babacan, A.E., Kırmacı, M.Z., Fırat Ersoy, A., Subaşı, B.M. (2019). Conceptual model of the Şavşat (Artvin/NE Turkey) Geothermal Field developed with hydrogeochemical, isotopic, and geophysical studies. *Geothermal Energy*, 7, 1-26. https://doi.org/10.1186/s40517-019-0128-5

Hatipoğlu Temizel, E., Gültekin, F., Ersoy Fırat, A. 2019. Rare earth elements and yttrium geochemistry of the geothermal fields in the eastern Black Sea Region (Ordu, Rize, Artvin), NE Turkey. *Bulletin of the Mineral Research and Exploration*, 160, 135- 153. https://doi.org/10.19111/bulletinofmre.502835

Hatipoğlu Temizel, E., Gültekin, F., Ersoy, A.F. (2020). Major, trace, and rare earth element geochemistry of the Ayder and İkizdere (Rize, NE Turkey) geothermal waters: Constraints for water–rock interactions. *Geothermics*, 86, 101810. https://doi.org/10.1016/j.geothermics.2020.101810

Jennejohn, D., Hines, B., Gawell, K., Blodgett, L. (2012). Geothermal: international market overview report. Geothermal Energy Association, Washington

Karslı, O., Aydin, F., Sadiklar, M. (2004). The morphology and chemistry of K-feldspar megacrysts from Ikizdere Pluton: evidence for acid and basic magma interactions in granitoid rocks, NE–Turkey. *Geochemistry,* 64(2), 155-170. https://doi.org/10.1016/j.chemer.2003.02.001

Karslı, O., Chen, B., Aydin, F., Şen, C. (2007). Geochemical and Sr–Nd–Pb isotopic compositions of the Eocene Dölek and Sariçiçek Plutons, Eastern Turkey: implications for magma interaction in the genesis of high-K calc-alkaline granitoids in a post-collision extensional setting. *Lithos*, *98*(1-4), 67-96. https://doi.org/10.1016/j.lithos.2007.03.005

Karslı, O., Dokuz, A., Uysal, İ., Aydin, F., Kandemir, R., Wijbrans, J. (2010). Generation of the Early Cenozoic adakitic volcanism by partial melting of mafic lower crust, Eastern Turkey: implications for crustal thickening to delamination. *Lithos*, *114*(1-2), 109-120. https://doi.org/10.1016/j.lithos.2009.08.003

Karslı, O., Ketenci, M., Uysal, İ., Dokuz, A., Aydin, F., Chen, B., Kandemir, R., Wijbrans, J. (2011). Adakite-like granitoid porphyries in the Eastern Pontides, NE Turkey: potential parental melts and geodynamic implications. *Lithos*, *127*(1-2), 354-372. https://doi.org/10.1016/j.lithos.2011.08.014

Karslı, O., Dokuz, A., Uysal, İ., Ketenci, M., Chen, B., Kandemir, R. (2012). Deciphering the shoshonitic monzonites with I-type characteristic, the Sisdaği pluton, NE Turkey: Magmatic response to continental lithospheric thinning. *Journal of Asian Earth Sciences,* 51, 45-62. https://doi.org/10.1016/j.jseaes.2012.02.003

Karakaya, N., Karakaya, M.C., Nalbantçılar, M.T., Yavuz, F. (2007). Relation between spring-water chemistry and hydrothermal alteration in the Şaplıca volcanic rocks, Şebinkarahisar (Giresun, Turkey). *Journal of Geochemical Exploration*, 93(1), 35-46. https://doi.org/10.1016/j.gexplo.2006.08.012

Karayel, G.K., Javani, N., Dincer, I. (2022). Effective use of geothermal energy for hydrogen production: A comprehensive application. *Energy*, 249, 123597. https://doi.org/10.1016/j.energy.2022.123597

Kaygusuz, A., Siebel, W., Ilbeyli, N., Arslan, M., Satir, M., Sen, C. (2010). Insight into magma genesis at convergent plate margins-a case study from the eastern Pontides (NE Turkey). *Neues Jahrbuch Fur Mineralogie-Abhandlungen,* 187(3), 265. https://doi.org/10.1127/0077-7757/2010/0178

Kaygusuz, A., Aydınçakır, E. (2011). Petrogenesis of a Late Cretaceous composite pluton from the eastern Pontides: the Dagbaşı pluton, NE Turkey. Neues Jahrbuch fur Mineralogie, Abhandlungen, 188(3), 211-233. https://doi.org/10.1127/0077-7757/2011/0201

Kaygusuz, A., Şen, C. (2011). Calc-alkaline I-type plutons in the eastern Pontides, NE Turkey: U–Pb zircon ages, geochemical and Sr–Nd isotopic compositions. *Geochemistry*, *71*(1), 59-75. https://doi.org/10.1016/j.chemer.2010.07.005

Kaygusuz, A., Arslan, M., Siebel, W., Sipahi, F., Ilbeyli, N. (2012a). Geochronological evidence and tectonic significance of Carboniferous magmatism in the southwest Trabzon area, eastern Pontides, Turkey. *International Geology Review*, *54*(15), 1776-1800. https://doi.org/10.1080/00206814.2012.676371

Kaygusuz, A., Arslan, M., İlbeyli, N., Sipahi, F. (2012b). Doğu Pontid kuzey zonu ve kuzey-güney zon geçişinde yüzeylenen Kretase-Paleosen yaşlı granitoyidik sokulumların petrokimyası, Sr-Nd-Pb-O izotop jeokimyası, jeokronolojisi ve jeodinamik gelişimi, Tübitak Çaydağ Project No: 109Y052 final report (Turkish with English Abstract), 175

Kaygusuz, A., Sahin, K. (2016). Petrographical, geochemical and petrological characteristics of Eocene volcanic rocks in the Mescitli area, Eastern Pontides (NE Turkey). *Journal of Engineering Research and Applied Science*, *5*(2), 473-486.

Kaygusuz, A., Aydincakir, E., Yucel, C., Atay, H.E. (2021a). Petrographic and geochemical characteristics of carboniferous plutonic rocks around Erenkaya (Gümüşhane, NE Turkey). *Journal of Engineering Research and Applied Science*, *10*(2), 1774-1788.

Kaygusuz, A., Arslan, M., Temizel, İ., Aydınçakır, E. (2021b). U–Pb zircon ages and petrogenesis of the Late Cretaceous I-type granitoids in arc setting, Eastern Pontides, NE Turkey. *Journal of African Earth Sciences*, *174*, 104040. https://doi.org/10.1016/j.jafrearsci.2020.104040

Ketin, İ. (1966). Tectonic units of Anatolia (Asia minor). Bulletin of the Mineral Research and Exploration, 66(66).

Koelbel, T., Genter, A. (2017). Enhanced geothermal systems: the Soultz-sous-Forêts project. In *Towards 100% Renewable Energy: Techniques, Costs and Regional Case-Studies* (pp. 243-248). Springer International Publishing. https://doi.org/10.1007/978-3-319-45659-1_25

Lachenbruch, A.H. (1979). Heat flow in the Basin and Range province and thermal effects of tectonic extension. *Geothermics and Geothermal Energy*, 34-50. https://doi.org/10.1007/BF00879732

Maden, N., Gelişli, K., Eyüboğlu, Y., Bektaş, O. (2009). Two-and-three-dimensional crustal thickness of the eastern pontides (NE Turkey). *Turkish Journal of Earth Sciences*, 18(2), 225-238. https://doi.org/10.3906/yer-0703-3

Maden, N. (2012). One-dimensional thermal modeling of the eastern pontides orogenic belt (NE Turkey). *Pure and Applied Geophysics,* 169, 235-248. https://doi.org/10.1007/s00024-011-0296-0

Maden, N. (2013). Geothermal structure of the eastern Black Sea basin and the eastern Pontides orogenic belt: Implications for subduction polarity of Tethys oceanic lithosphere. *Geoscience Frontiers*, *4*(4), 389-398. https://doi.org/10.1016/j.gsf.2013.02.001

Maden, N., Akaryalı, E. (2015). Gamma ray spectrometry for recognition of hydrothermal alteration zones related to a low sulfidation epithermal gold mineralization (eastern Pontides, NE Türkiye). *Journal of Applied Geophysics*, *122*, 74-85. https://doi.org/10.1016/j.jappgeo.2015.09.003

Okay, A. İ., Şahintürk, Ö. 1997. Pulur bölgesi stratigrafisi ve tektoniği (Bayburt, Doğu Pontidler). MTA Dergisi, 119, 1-22.

Okay, I.A., Tüysüz, O. (1999). Tethyan sutures of northern Türkiye. Geological Society, London, Special Publication, 156, 475-515. https://doi.org/10.1144/GSL.SP.1999.156.01.22

Omenda, P., Varun, C., Chandrasekharam, D. (2012) High heat generating granites of East Africa: Possible EGS sources. In: Proceedings of the 4th African Rift Geothermal Conference Nairobi, Kenya, 1–4

Özkan, R., Şener, M., Helvaci, C., Şener, M.F. (2011). Aliağa (İzmir) jeotermal alanındaki hidrotermal alterasyonlar ve termal sularla ilişkisi. *Yerbilimleri*, 32(1), 141-168.

Özkaptan, M. (2019). Crustal disequilibrium of the central Pontides (northern Turkey) due to oroclinal bending revealed by gravity modelling. *Journal of Asian Earth Sciences*, 186, 104058. https://doi.org/10.1016/j.jseaes.2019.104058

Pamuk, E. (2019). Investigating edge detection, Curie point depth, and heat flow using EMAG2 magneticand EGM08 gravity data in the northern part of Eastern Anatolia, Turkey. *Turkish Journal of Earth Sciences*, 28(6), 805-821. https://doi.org/10.3906/yer-1902-34

Pan, S. Y., Gao, M., Shah, K. J., Zheng, J., Pei, S. L., Chiang, P. C. (2019). Establishment of enhanced geothermal energy utilization plans: Barriers and strategies. *Renewable energy*, *132*, 19-32. https://doi.org/10.1016/j.renene.2018.07.126

Rice, S.P., Robertson, A.H. Ustaömer, T. (2006). Late Cretaceous-Early Cenozoic tectonic evolution of the Eurasian active margin in the Central and Eastern Pontides, northern Turkey. Geological Society, London, Special Publications, 260(1), 413-445. https://doi.org/10.1144/GSL.SP.2006.260.01.1

Rybach, L. (1976). Radioactive heat production: A physical property determined by the chemistry. In: RGI Strens, ed. *The Physical and Chemistry of Minerals and Rocks*. New York, USA: Wiley-Interscience Publication; 1976, 245-276.

Şen, C., Arslan, M., Van, A. (1998). Geochemical and petrological characteristics of the Eastern Pontide Eocene (?) alkaline volcanic province, NE Turkey. *Turkish Journal of Earth Sciences*, *7*(3), 231-240.

Şener, M.F., Şener, M., Uysal, I.T. (2017). The evolution of the Cappadocia Geothermal Province, Anatolia (Turkey): geochemical and geochronological evidence. *Hydrogeology Journal,* 25(8), 2323-2345. https://doi.org/10.1007/s10040-017-1613-1

Şener, M.F. (2018). Akhüyük (Konya) jeotermal alanındaki hidrotermal akışkan dolaşımı ve traverten oluşum mekanizması, Orta Anadolu, Türkiye. *Türkiye Jeoloji Bülteni*, 61(2), 193-206. https://doi.org/10.25288/tjb.437943

Şener, M.F. (2019). A new approach to Kırşehir (Turkey) geothermal waters using REY, major elements and isotope geochemistry. *Environmental Earth Sciences*, 78, 1-15. https://doi.org/10.1007/s12665-019-8068-8

Şener, M.F., Baba, A. (2019). Geochemical and hydrogeochemical characteristics and evolution of Kozaklı geothermal fluids, Central Anatolia, Turkey. *Geothermics,* 80, 69-77. https://doi.org/10.1016/j.geothermics.2019.02.012

Şener, M.F., Baba, A., Uzelli, T., Akkuş, İ., Mertoğlu, O. (2022). Türkiye Jeotermal Kaynaklar Strateji Raporu, Maden ve Petrol İşleri Genel Müdürlüğü, 1-149.

Şener, M. F., Uzelli, T., Akkuş, İ., Mertoğlu, O., Baba, A. (2023). The potential, utilization, and development of geothermal energy in Türkiye. *Bulletin of the Mineral Research and Exploration* 171, 69-90. https://doi.org/10.19111/bulletinofmre.1229381

Şengör, A.M.C., Yilmaz, Y. (1981). Tethyan evolution of Turkey: a plate tectonic approach. *Tectonophysics,* 75(3-4), 181-241. https://doi.org/10.1016/0040-1951(81)90275-4

Tester, J.W., Anderson, B.J., Batchelor, A.S., Blackwell, D.D., DiPippo, R., Drake, E.M., Garnish, J., Livesay, B., Moore, M.C., Nichols, K., Petty, S. (2006) The future of geothermal energy. Massachusetts Institute of Technology. 358.

Temizel, İ., Arslan, M., Ruffet, G., Peucat, J.J. (2012). Petrochemistry, geochronology and Sr–Nd isotopic systematics of the Tertiary collisional and post-collisional volcanic rocks from the Ulubey (Ordu) area, eastern Pontide, NE Turkey: implications for extension-related origin and mantle source characteristics. *Lithos*, *128*, 126-147. https://doi.org/10.1016/j.lithos.2011.10.006

Temizel, İ., Arslan, M., Yücel, C., Abdioğlu, E., Ruffet, G. (2016). Geochronology and geochemistry of Eocene-aged volcanic rocks around the Bafra (Samsun, N Turkey) area: Constraints for the interaction of lithospheric mantle and crustal melts, *Lithos*, 258-259, 92-114. https://doi.org/10.1016/j.lithos.2016.04.023

Temizel, I., Yazar, E.A., Arslan, M., Kaygusuz, A., Aslan, Z. (2018). Mineral chemistry, whole-rock geochemistry and petrology of Eocene I-type shoshonitic plutons in the Gölköy area (Ordu, NE Turkey). *Bulletin of the Mineral Research and Exploration*, *157*(157), 121-152. https://doi.org/10.19111/bulletinofmre.371623

Tokel, S. (1981). Plaka tektoniğinde magmatik yerleşimler ve jeokimya: Türkiye'den örnekler. Yeryuvarı ve insan, 6(3–4), 55-65.

Topuz, G., Altherr, R., Siebel, W., Schwarz, W.H., Zack, T., Hasözbek, A., Barth, M., Satır, M., Şen, C., (2010). Carboniferous high-potassium I-type granitoid magmatism in the Eastern Pontides: the Gümüşhane pluton (NE Turkey). *Lithos*, *116*(1-2), 92-110. https://doi.org/10.1016/j.lithos.2010.01.003

Türkiye National Energy Plan (2022). Republic of Türkiye Ministry of Energy and Natural Resources, https://enerji.gov.tr/Media/Dizin/EIGM/tr/Raporlar/TUEP/T%C3%BCrkiye_National_Energy_Plan.pdf

Ustaömer, T., Robertson, A.H.F., (1996). Paleotethyan tectonic evolution of the North Tethyan margin in the central Pontides, N Turkey. In International symposium on the geology of the Black Sea Region, Proceedings-I (Vol. 24, p. 33).

Van Schmus, W.R. (1995). Natural radioactivity of the crust and mantle. In *Global earth physics: A handbook of physical constants* (Vol. 1, pp. 283-291). Washington, DC: American Geophysical Union.

Verzhbitskii, E.V. (2002). Heat flow and the age of the lithosphere in the Black Sea. *Oceanology*, *42*(6), 834-839. https://doi.org/10.1134/S0001437006020147

Vigneresse, J.L., Jolivet, J., Cuney, M., Bienfait, G. (1987). Heat flow, heat production and granite depth in western France. *Geophysical Research Letters*, 14(3), 275-278. https://doi.org/10.1029/GL014i003p00275

Vural, A., Gundogdu, A., (2020). High-fluoride risk and toxicity in surface waters in Gumushane-Gokdere valley drainage network (NE Turkey). *Journal of Engineering Research and Applied Science*, 9(1), 1323-1334.

Yilmaz, S., Boztuğ, D. (1996). Space and time relations of three plutonic phases in the Eastern Pontides, Turkey. *International Geology Review,* 38(10), 935-956. https://doi.org/10.1080/00206819709465373

Yılmaz Sahin, S., Güngör, Y. and Boztug, D. (2004). Comparative petrogenetic investigation of composite Kaçkar Batholith granitoids in Eastern Pontide magmatic arc-Northern Turkey. *Earth, planets and space*, *56*(4), 429-446. https://doi.org/10.1186/BF03352496

Yılmaz, Y., Tüysüz, O., Yiğitbaş, E., Genç, Ş.C., Şengör, A.M.C. (1997). Geology and tectonic evolution of the Pontides, in Regional and petroleum geology of the Black Sea and surrounding region. The American Association of Petroleum Geologists. 68, 183-226. https://doi.org/10.1306/M68612C11

Yücel, C. (2019). Geochronology, geochemistry, and petrology of adakitic Pliocene–Quaternary volcanism in the Şebinkarahisar (Giresun) area, NE Turkey. *International Geology Review*, 61(6), 754-777. https://doi.org/10.1080/00206814.2018.1461029

Zhang, Y.J., Li, Z.W., Guo, L.L., Gao, P., Jin, X.P., Xu, T.F. (2014). Electricity generation from enhanced geothermal systems by oilfield produced water circulating through reservoir stimulated by staged fracturing technology for horizontal wells: A case study in Xujiaweizi area in Daqing Oilfield, China. *Energy*, 78, 788-805. https://doi.org/10.1016/j.energy.2014.10.073

Zhang, C., Feng, Q., Zhang, L., Qin, S., Jiang, G., Hu, J., Hu, S., Huang, R., Zhang, H. and Hassan, M., 2022. Characteristics of Radiogenic Heat Production of Widely Distributed Granitoids in Western Sichuan, Southeast Tibetan Plateau. *Lithosphere*, 4165618. https://doi.org/10.2113/2022/4165618