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The Relationship between Some Geothermal Sources near the Edremit Fault (Balıkesir, Türkiye) and Active Tectonics

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Abstract:
This study determines the behavior of the Edremit Fault in northwestern Anatolia through kinematic analysis of fault assemblies and focal mechanism solutions of earthquakes. It also reveals the relationship between the physico-chemical properties of hot springs in nearby geothermal areas and their behavior before, during, and after a potential earthquake, and active tectonics. The Edremit Fault and its surrounding area are among the regions in Turkey with high earthquake potential. The Edremit Fault, located in this area, has produced a significant earthquake in the past (1944; M: 6.8). Kinematic analysis of data obtained from fault planes in the study area revealed that the Edremit Fault exhibits normal faulting with oblique strike-slip movement, trending north-northeast-southeast, and a right-lateral strike-slip component under an extensional regime. Some earthquakes in the instrumental period in the region also exhibit a normal faulting model consistent with the course of this fault. In February, May, September, and December of 2022, and January of 2023, in-situ measurements were taken at four different hot springs (Güre-Heating Center (G-1), Güre-Adrina Thermal Hotel (G-2), Edremit-Entur Thermal Hotel (Derman Spring) (E-1), and Edremit-Adramis Thermal Hotel (Bostancı Village Spring) (E-2)) for pH, temperature (T), electrical conductivity (EC). Water samples were also collected from the hot springs for major anion and cation analyses (Ca, Mg, Na, K, HCO_3, SO_4 and Cl). During the sampling period, 12 earthquakes greater than magnitude 4 (Mw) occurred on land and at sea in and around the region. The physico-chemical changes experienced by the geothermal resources during and after these earthquakes are being evaluated.

Keywords: *Geothermal energy, hydrogeochemistry, earthquakes, active faults, kinematics*

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I. INTRODUCTION

The study area is located in and around the Edremit district of Balıkesir province in northwestern Anatolia (Figure 1). Geothermal systems worldwide are found on mid-ocean ridges, plate boundaries where active tectonism occurs, and on volcanic islands. Geothermal resources have been used for health purposes and heating throughout human history. At the beginning of the century, in Italy in 1904, electricity production from geothermal waters began. Turkey is rich in geothermal areas. The first geothermal studies began in the 1960s under the auspices of the MTA (Mineral Research and Exploration Institute), and to date, 227 geothermal fields have been inventoried (TJD, 2015). Furthermore, there are 1500 hot springs and wells in these areas. Turkey has approximately 2000 hot and mineral water sources. The temperatures of these sources range from 20-287°C. These areas are mainly located along the North Anatolian Fault, in the volcanic regions of Central and Eastern Anatolia, and in the horst-graben structures of Western Anatolia (Akkuş et al., 2005).

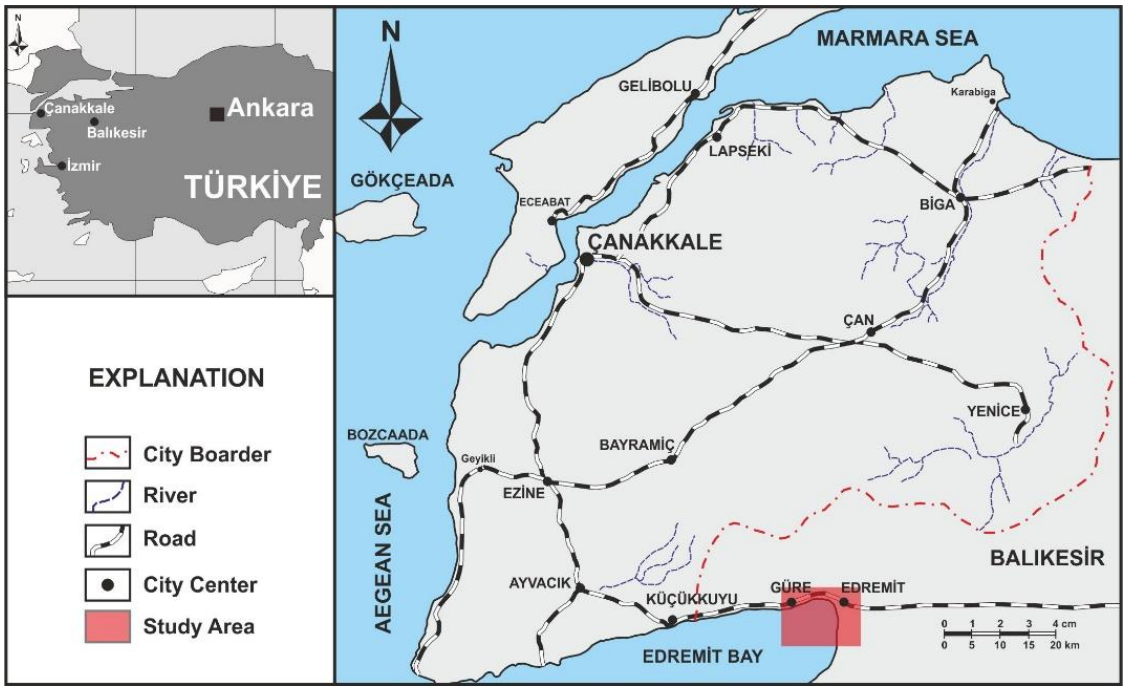


Figure 1. Location map of the study area.

In this study, fault planes were measured, strike-slip movements were determined, and kinematic analysis of fault clusters was performed in areas where the Edremit fault, which is also actively shown on the Active Fault Map of Turkey, is exposed. Additionally, four hot springs located along the Edremit fault were identified. These hot springs are E-1 (Edremit-Entur Thermal Hotel Derman Spring), E-2 (Edremit-Adramis Thermal Hotel Bostancı Spring), G-1 (Güre-Heating Center), and G-2 (Güre-Adrina Thermal Hotel). In-situ measurements and water sampling were conducted at these four hot springs located along the Edremit fault in five different periods between February 2022 and January 2023.

II. MATERIALS AND METHODS

Multiple active fault segments exist on the Biga Peninsula, and the movement of these active faults has caused hot springs to reach the surface through cracks, creating geothermal fields. Periodic measurements were taken in the Edremit (Balıkesir) geothermal field, and water samples were collected from identified hot spring sources through on-site measurements. The results were used to investigate whether there was a change in the physico-chemical properties of geothermal waters before and after a tectonic movement. In addition, fault kinematic analyses were performed to determine the current characteristics of the Edremit Fault.

During field studies, on-site and immediate measurements were taken at the hot springs using a Eutech Cybercan PCD 650 pH-conductivity-ion meter. These on-site measurements included physical parameters such as electrical conductivity (EC), pH and temperature (T°C). Major anion and cation analyses (Ca, Mg, Na, K, HCO_3, SO_4, and Cl) were performed on the collected water samples at the Central Laboratory of Çanakkale Onsekiz Mart University.

III. RESEARCH FINDINGS

III.1. Geology of the Study Area and Its Surroundings

The study area and its immediate vicinity geologically represent the southern part of the Kazdağları Mountains. This section is currently bordered by the Edremit Fault Zone. The basement of the study area consists of the Paleozoic-aged Alakeçili mylonite zone, Sütüven Formation, and Mermer member, all belonging to the Kazdağ Group (Okay, 1987; Okay et al., 1990; Duru et al., 2004; Yüzer and Tunay, 2012). The Triassic-aged Karakaya Formation rests unconformably on top of the basement rocks (Bingöl, 1968; Bingöl et al., 1973). The Cretaceous-aged Çetmi mélange rests tectonically on this basement (Okay et al., 1990). The Upper Oligocene-Lower Miocene Hallaçlar volcanic (Ercan et al., 1995) and Oligo-Miocene granodiorites (Duru et al., 2004) are emplaced, cutting through all the older units. Unconformably, Quaternary alluvium and coastal sediments overlie all these units (Figure 3).

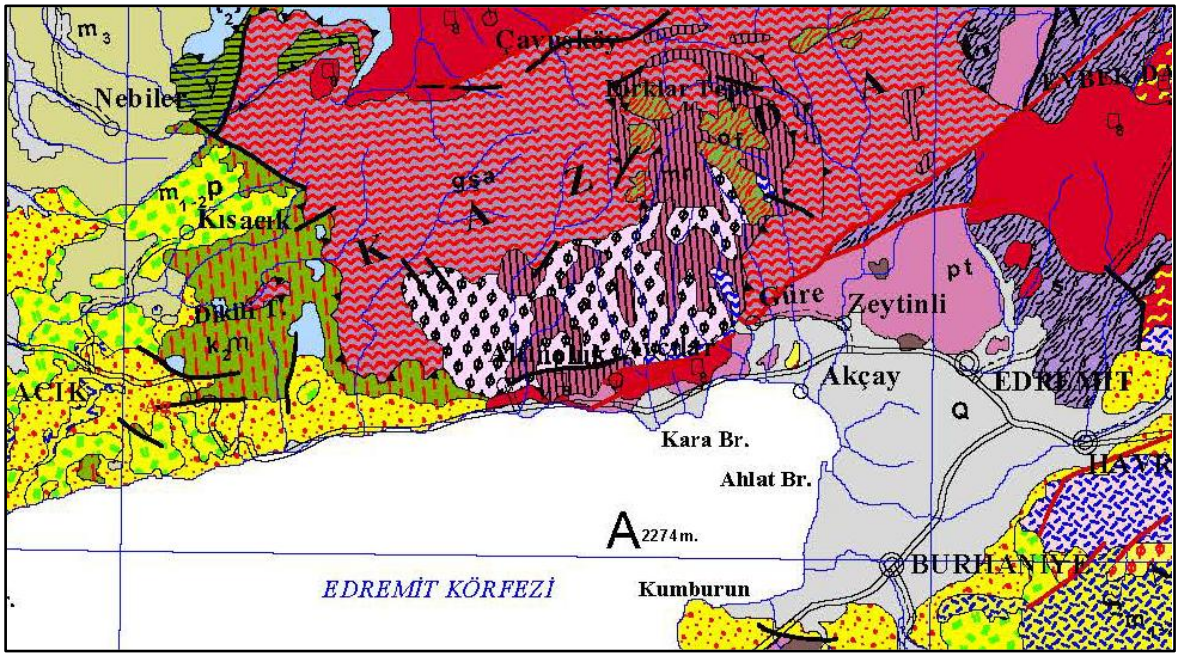


Figure 2. Geological map of the study area and its surroundings (MTA, 2002).

III.2. Active Tectonics, Seismicity and Kinematic Characteristics of the Study Area and Its Surroundings

The study area is located between the Gulf of Edremit and Mount Ida (Kazdağı). The Gulf of Edremit is a young, tectonically active basin situated in the northwestern Aegean, between the central and southern branches of the North Anatolian Fault, with its northern coast controlled by NNE-SW trending normal faults (Alpar and Yaltırak, 2002). The subsidence of the Gulf of Edremit and the uplift of the Mount Ida massif are influenced by a local N-S stress caused by the counterclockwise rotation of the Gulf of Edremit block by NE-SW trending strike-slip faults (Alpar and Yaltırak, 2002). Mount Ida corresponds to an asymmetrically uplifted horst north of the Gulf of Edremit graben. The northern coast of the Gulf of Edremit is also uplifted by the stepped faults formed by this system, while the central part of the gulf is subsiding in the same way. The Güre-Ilıca and Kavlaklar-Yassıçalı faults located in the study area are step-shaped normal faults that cause the uplift of Mount Kazdağı and the subsidence of the Edremit Gulf (Alpar and Yaltırak, 2002). Yaltırak (2003) describes the Edremit Fault as extending parallel to the coast in an ENE-WSW direction and bordering the Edremit Gulf from the north (Figure 3).

Figure 3. Active fault map of the study area and its surroundings (Emre and Doğan, 2010).

22 kinematic fault plane measurements were made on the Edremit fault in the study area (Figure 4). The common inverse solution of these faults shows that the Edremit fault developed under an extensional regime where the smallest principal stress axis is in the horizontal plane and on the outer arc (σ3, 209/17) and the largest principal stress axis is in the vertical plane and at the center (σ1, 343/67). It was determined to be a fault with oblique normal faulting characteristics, developing under a NNW-SSW oriented extensional regime and having approximately E-W orientation and a right-lateral strike-slip component (Figure 5).

Figure 4. Fault planes where kinematic measurements were taken in the study area (Altınoluk-Güre Highway)

According to kinematic analysis, the Edremit fault is observed to have a normal fault character with a NNW-SSE extensional regime and a right-lateral strike-slip component in the E-W direction (Figure 5).

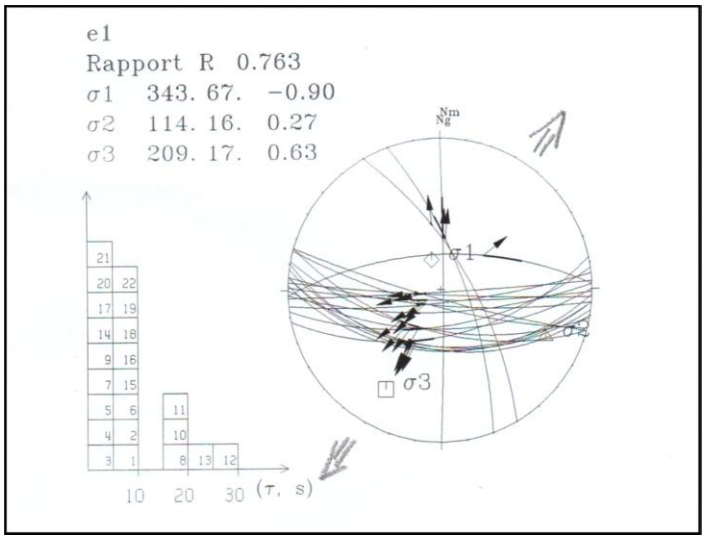


Figure 5. Lower hemisphere stereoplots showing normal faulting data measured in the study area and the results determined by Carey's (1979) inversion method.

An earthquake of magnitude M:6.8 occurred on the Edremit Fault, located in the study area, on June 10, 1944 (Figure 6). According to field observations (Yaltırak, 2003) and reflected marine seismic data (Altınok et al., 2012), the rupture of the 1944 earthquake is approximately 35 km long. The average focal depths of earthquakes occurring in the North Aegean Region vary between 5 and 10 km, reaching up to 10-12 km at most (Taymaz et al., 1991; Altınok, 2013). Tectonic activity continued in the vicinity, particularly in Ayvacık and west of the Edremit fault, with the Mw=5.4 earthquake that occurred on February 6, 2017 (Özden et al., 2018). Furthermore, on the Bergama fault, which extends just southeast of the Edremit fault, there was another earthquake of magnitude 6.5 on September 22, 1939, which also exhibits a normal faulting pattern.

According to USGS data, an earthquake with an instrumental magnitude of Mw=6.3 occurred off the coast of Lesbos-Karaburun on June 12, 2017. The fault plane solution showed normal faulting with a K 66 W, 57 SW and 82 (slip vector) orientation. Following the main shock, 17 aftershocks with magnitudes ranging from 4.0 to 5.3 occurred. These earthquakes and their solutions indicate that this region has a tectonic regime dominated by normal faults formed within an extensional regime.

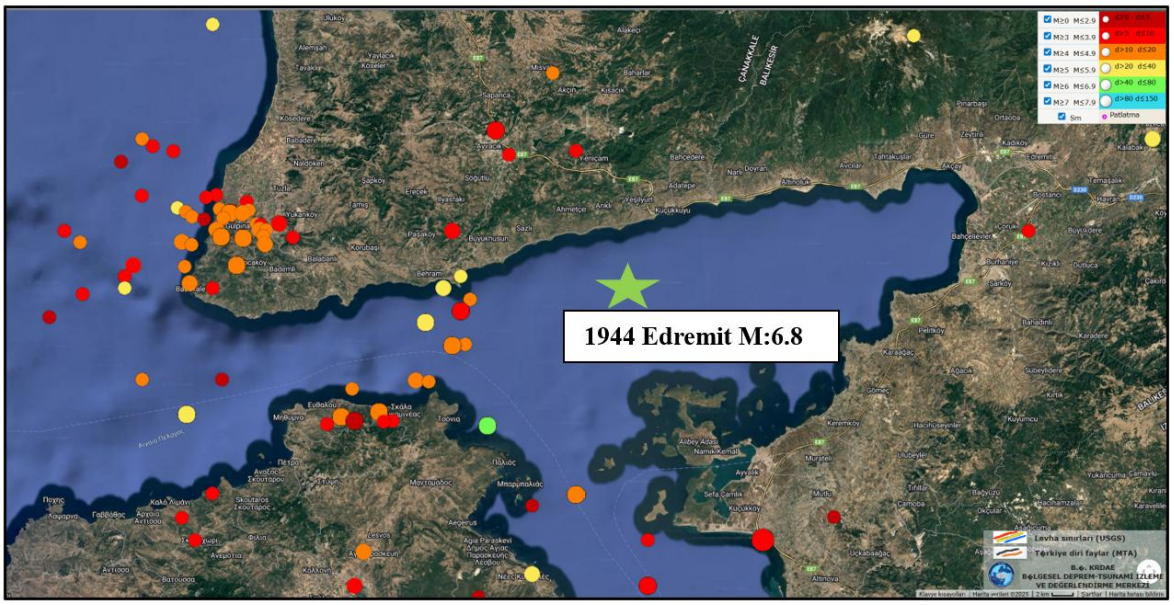


Figure 6. M>4 earthquakes that occurred in the study area and its vicinity between 1900 and 2023 (BDTİM).

During the period between January 2022 and January 2023, when this study was conducted, there were three seismic events in the north of Lesbos Island: two on January 7, 2023, with magnitudes of M=4.7 and 4.6, and one on January 10, 2023, with a magnitude of M=4.9, followed by numerous aftershocks (Figure 7).

Figure 7. Earthquakes that occurred on Lesbos Island between 07.01.2023 and 10.01.2023 during this study period (BDTİM).

III.3. Hydrogeochemical Characteristics of Geothermal Fields Located in the Study Area

Four different hot springs located along the Edremit fault were identified in the study area. These hot springs are the Güre Geothermal Heating Center (G-1), the Güre Adriana Thermal Hotel (G-2), the Edremit Entur Thermal Hotel (Derman spring) (E-1), and the Edremit Adramis Hotel (Bostancı Village spring) (E-2) located in the Güre geothermal area (Figure 8). On-site measurements and water sampling studies were conducted at these hot springs in five different periods between February 2022 and January 2023.

Figure 8. Hot springs where on-site measurement and sampling were conducted in the study area (Google Earth).

G-1 hot spring is located in Güre town, Edremit district, Balıkesir province. The hot water comes from a borehole that supplies hot water to the heating center in the town (Figure 9). G-2 hot spring comes from a hot water borehole belonging to the Adrina Thermal Hotel in Güre town (Figure 9). E-1 hot spring is a hot spring belonging to the Entur Thermal Hotel, located south of Edremit district, Balıkesir province (Figure 9). E-2 hot spring comes from a hot spring belonging to the Adramis Thermal Hotel, located south of Edremit district, Balıkesir province (Figure 9).

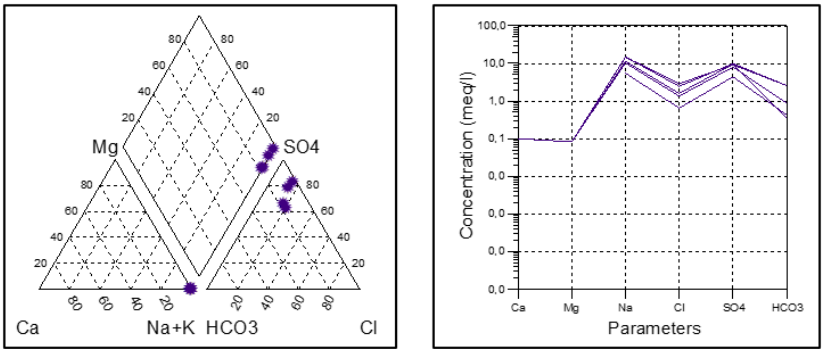
Figure 9. Hot water sources in the study area.

In-situ measurements and water sampling were conducted at the hot springs in the study area during five different periods between February 2022 and January 2023. The physical and chemical properties of the hot springs are given in Table 1.

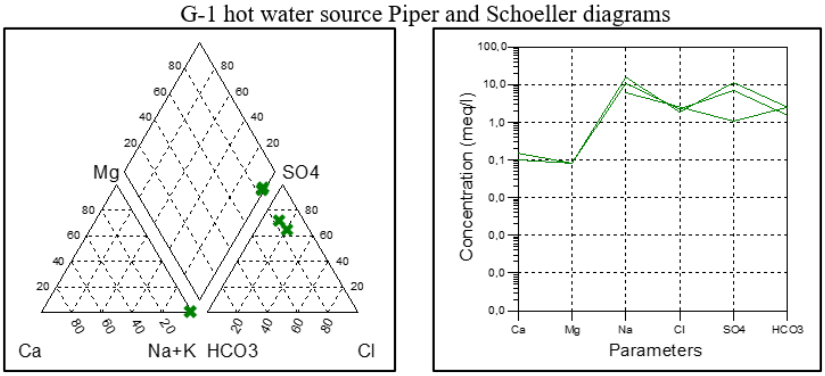
Table 1. Physical and chemical properties of hot springs in the study area.

Sample No	Location	Date	T (°C)	pH	EC (µS)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	Cl (mg/l)	SO_4 (mg/l)	HCO_3 (mg/l)
G-1	Güre	16.02.2022	80,50	7,93	1486,00	343,00	5,00	2,99	1,81	87,75	476,65	157,00
		19.05.2022	59,70	7,72	1087,00	235,87	6,12	2,06	1,25	48,87	385,77	54,00
		15.09.2022	60,20	7,44	1176,00	337,64	6,73	2,94	1,78	103,85	442,10	157,00
		18.12.2022	79,10	7,27	1452,00	126,25	2,87	1,10	0,67	23,92	212,46	26,00
		8.01.2023	77,80	7,56	1473,00	264,71	5,20	2,31	1,40	57,16	459,11	21,00
G-2	Güre	16.02.2022	60,50	7,13	1568,00	247,09	6,90	2,15	1,31	79,35	335,73	94,00
		19.05.2022	61,80	6,96	1549,00	140,44	4,80	1,22	0,74	90,35	51,89	153,00
		15.09.2022	61,10	7,15	1617,00	359,56	8,20	3,14	1,90	66,75	541,65	49,00
E-1	Edremit	16.02.2022	41,80	7,61	987,10	184,19	3,80	1,61	3,07	50,96	250,61	85,00
		19.05.2022	39,70	7,30	1105,00	160,83	4,12	1,40	7,24	42,00	216,92	80,00
		15.09.2022	41,90	7,32	1216,00	248,32	7,80	2,16	3,13	56,12	386,28	72,00
		18.12.2022	38,90	6,80	1041,00	206,69	3,50	2,06	3,60	51,24	309,33	68,00
		8.01.2023	38,40	7,37	994,60	193,97	6,45	1,69	10,25	47,88	291,11	64,00
E-2	Edremit	16.02.2022	39,00	7,89	853,60	253,72	5,65	2,21	1,34	51,72	419,08	53,00
		19.05.2022	40,50	7,27	832,10	170,34	4,48	1,48	0,90	42,44	239,72	76,00
		15.09.2022	39,80	7,27	773,60	225,05	5,28	1,97	1,19	56,40	339,69	70,00
		18.12.2022	38,30	6,72	798,70	164,77	4,78	1,44	0,87	40,86	223,80	85,00
		8.01.2023	39,50	6,33	809,20	168,60	4,98	1,47	0,89	41,55	232,93	82,00

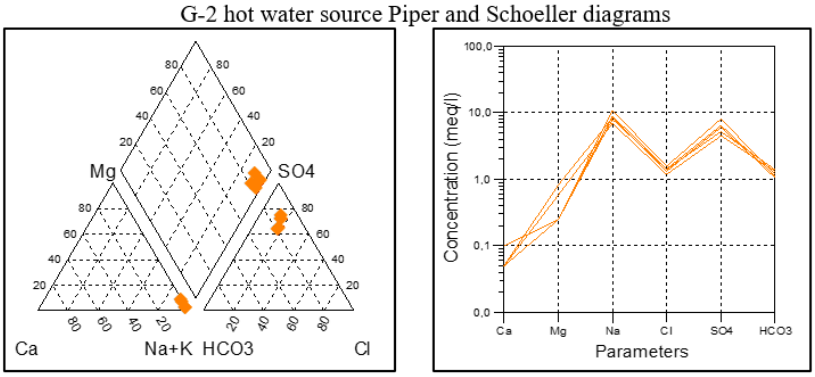
According to these data, the major anion/cation analysis results of the hot springs in the study area were plotted on Piper and Schoeller hydrogeochemical diagrams to determine the water type. When the water types in the area were examined, hot springs G-1, E-1, and E-2 reflected the Na-SO_4 type, while hot spring G-2 reflected the Na-SO_4-Cl type. Due to the similar characteristics they exhibit among themselves, these four separate hot springs can be interpreted as having a common origin and belonging to the same reservoir and recharge area (Figure 10). The cation configurations in the hot springs in the study area are Na+K>Ca>Mg and the anion configurations are SO_4>HCO_3>Cl.



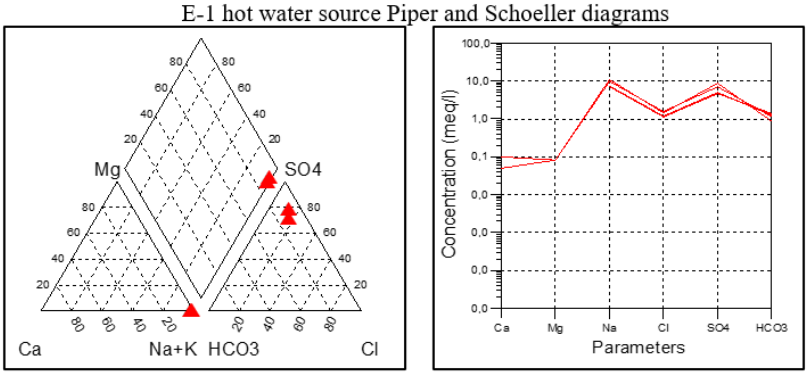
G-1 hot water source Piper and Schoeller diagrams



G-2 hot water source Piper and Schoeller diagrams



E-1 hot water source Piper and Schoeller diagrams



E-2 hot water source Piper and Schoeller diagrams

Figure 10. Piper and Schoeller Diagrams of hot springs in the study area.

IV. CONCLUDING REMARKS

22 kinematic fault plane measurements were taken in the study area. The common inverse solution of these faults shows that the Edremit Fault developed under an extensional regime where the smallest principal stress axis is in the horizontal plane and on the outer arc (σ3, 209/17) and the largest principal stress axis is in the vertical plane and at the center (σ1, 343/67). It was determined to be a fault with oblique normal faulting characteristics, developing under a NNW-SSW oriented extensional regime, approximately east-west oriented, and having a right-lateral strike-slip component.

Fieldwork and in-situ measurements and water sampling were conducted at hot springs along the Edremit fault in the thesis project area in February 2022, May 2022, September 2022, December 2022, and January 2023. These are the G-1 (Güre-Heating Center), G-2 (Güre-Adrina Thermal Hotel), E-1 (Edremit-Entur Thermal Hotel (Derman Spring)), and E-2 (Edremit-Adramis Thermal Hotel (Bostancı Village Spring)) hot springs.

According to these data, the thermal waters have temperatures between 39 and 80°C. Their pH values range from a minimum of 6.33 to a maximum of 7.93. Their electrical conductivity values range from a minimum of 773.60 to a maximum of 1617.00 µs.

During the sampling period, 15 earthquakes with a magnitude greater than 4 (Mw) occurred on land and at sea in and around the region. Three of these earthquakes occurred just north of Lesbos Island (50-70 km from the sources) between January 6-10, 2023. It is estimated that the geothermal resources underwent some physico-chemical changes during and after these earthquakes.

The thermal waters were affected by two earthquakes with magnitudes of M=4.7 and 4.6 between January 7th and 10th, 2023, and another earthquake with a magnitude of M=4.9 on January 10th, 2023. During these earthquakes, a decrease in HCO_3 values was observed in the G-1 hot spring. A decrease in pH and HCO_3 values was observed in the E1 hot spring. In the E-2 hot spring, a decrease in pH and an increase in HCO_3 values were observed in the physicochemical properties of the water.

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