International Refereed Journal of Engineering and Science (IRJES)
ISSN (Online) 2319-183X, (Print) 2319-1821
Volume 14, Issue 4 (Jul. – Aug. 2025), PP. 172-187

Hydrogeocemical Features of Some Geothermal Sources in Köyceğizand Dalaman (Muğla-Türkiye)

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Abstract:*The study area is located within the borders of the Köyceğiz-Dalaman districts in the southeast of Muğla Province in SW Anatolia. The region is highly active in terms of instrumental earthquakes and is also rich in geothermal systems. A large part of this region remains at risk of earthquakes today, as it was in the past. The NW-SE-trending Milas Fault, the Yatağan Fault, the Muğla Fault, and the E-W-trending Gökova Fault Zone, which borders Gökova Bay to the south, are the most important active faults in the region and its surrounding areas. Furthermore, in addition to these faults, the area is known to contain many other active tectonic elements. The region is also very rich in geothermal systems and contains many geothermal fields, including Yatağan (Bozhöyük), Bodrum (Karaada), Datça (Ilıca, Gölbaşı), Köyceğiz (Sultaniye), Dalyan (DelibeyGirmesi, RızaçavuşGirmesi, Gelgirme), Sarıgerme (Çürükardı), and Fethiye (Gebeler). Most of these geothermal fields are located on active fault zones. A monitoring study (on-site measurements and water sampling) lasting approximately one year was conducted between September 2021 and October 2022 from the hot springs identified in the Sultaniye (S-1) and DelibeyGirmesi (S-2) (Köyceğiz), and KapukargınSpring (K-1) and Pool (K-2) (Dalaman) geothermal fields, to reveal the hydrogeochemical properties of the hot springs.*
Keywords: ***Geothermal, Hydrogeochemistry, Muğla, Active Fault***

Date of Submission: 10-08-2025 Date of acceptance: 24-08-2025

I. INTRODUCTION

Geothermal energy, one of the renewable energy sources, has been accepted as an energy source that stands out with its non-polluting, sustainable, domestic and environmentally friendly features when appropriate technologies are used, although it does not have the potential to compete with fossil fuels, which are among the primary energy sources.

The province of Muğla (SW Anatolia) is home to numerous active faults, shown as active on the Active Fault Map of Turkey, and numerous geothermal fields developed as a result of these faults. The Karaova-Milas and Muğla-Yatağan Fault Zones, trending approximately NW-SE, and the Gökova Fault Zone, trending approximately E-W, which borders Gökova Bay to the south, are the most important active faults in the region [5]. In addition to these faults, the area is also known to contain numerous active tectonic elements.

The region is also rich in geothermal systems and includes numerous geothermal fields—Yatağan (Bozhöyük), Bodrum (Karaada), Datça (Ilıca, Gölbaşı), Köyceğiz (Sultaniye), Dalyan (DelibeyGirmesi, RızaçavuşGirmesi, Gelgirme), Sarıgerme (Çürükardı), and Fethiye (Gebeler). Many of these geothermal fields are located on active fault zones.

In this study, on-site measurements (pH, conductivity-EC, and temperature-T^0C) and geochemical analyses (Ca, Mg, Na, K, Cl, SO_4, HCO_3, and B) of hot water samples were carried out in four different geothermal hot springs located in the Köyceğiz and Dalaman districts of Muğla province to reveal the hydrogeochemical properties of the hot springs. Sampling and on-site measurements were carried out regularly at certain periods between September 2021 and October 2022.

II. MATERIALS and METHODS

In this study, hot springs associated with active fault lines were identified in geothermal areas located in the Köyceğiz and Dalaman districts of Muğla province. These hot springs are the Sultaniye thermal spring (S-1) and DelibeyGirmesi (S-2) in the Sulataniye geothermal field in Köyceğiz district, and the Spring (K-1) and Pool (K-2) hot springs in the Kapukargın geothermal field in Dalaman district. On-site measurements and water sampling were carried out at the hot springs in four geothermal fields determined in the field in seven sampling periods over a year. pH, conductivity (EC), and temperature (T^0C) measurements were taken at the beginning of the springs. Anion and cation (Ca, Mg, Na, K, Cl, SO_4, HCO_3, and B) analyses were conducted at the Environmental Measurement and Analysis Laboratory of GEMAR Environmental Measurement and Analysis Occupational Health and Safety Geology Mining Construction. Industry and Trade Ltd. Company.

III. RESULTS and DISCUSSION

The study area is located in SW Anatolia, within the borders of Muğla province, in an area limited to Köyceğiz in the north and Dalaman districts in the south (Figure 1).

Fig. 1. Location map of the study area

In this study, on-site measurements and sampling studies were carried out regularly at certain periodic times from 4 hot springs identified in the region between September 2021 and October 2022. These hot springs are the Sultaniye hot spring (S-1) and DelibeyGirmesi (S-2) in the Sultaniye geothermal field in Köyceğiz district, and the Spring (K-1) and Pool (K-2) hot water springs in the Kapukargın geothermal field in Dalaman district (Figure 2). On-site measurements and sampling studies were carried out in 7 different periods (September 2021, October 2021, February 2022, April 2022, June 2022, September 2022 and October 2022) at these hot springs.

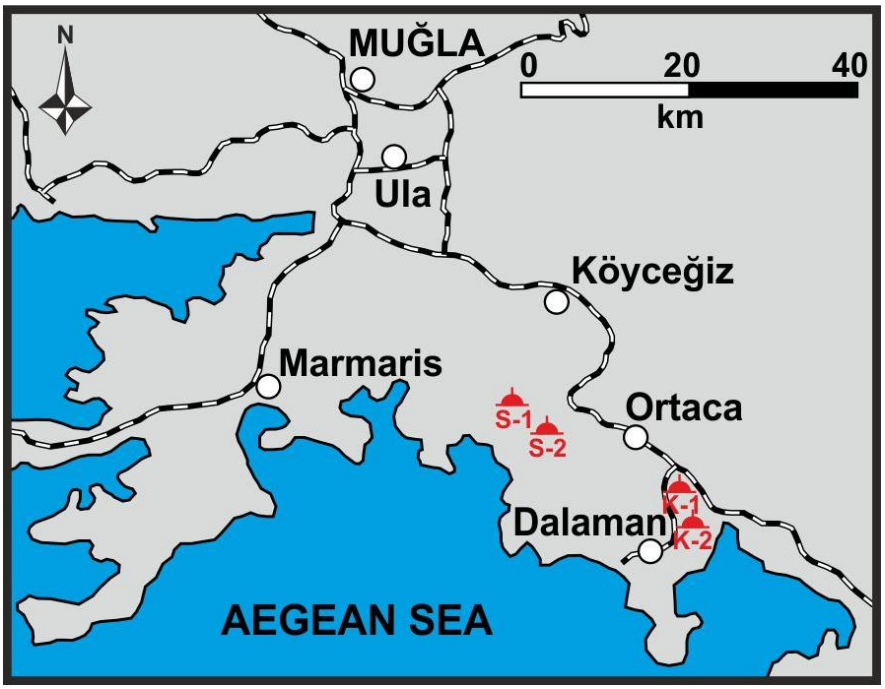

Fig. 2. Hot water springs identified in the study area

III.1. Hydrogeochemical Properties of Geothermal Fields in the Study Area

In this study, periodic on-site measurements and water sampling were conducted from hot springs identified in the Sultaniye (Köyceğiz) and Kapukargın (Dalaman) geothermal fields in Muğla province during seven different periods between September 2021 and October 2022.

III.1.1. Köyceğiz-Sultaniye Geothermal Field

The Sultaniye geothermal field is located in the southeast of Muğla Province, approximately 10 km south and southwest of the Köyceğiz district. The area contains springs with temperatures ranging from 34 to 41^{0}C (Table 1) [1]. The hot spring is used only for bathing purposes in the Sultaniye thermal springs region.

Table 1. Resources in the Köyceğiz geothermal field [1]

Spring	Temperature (T^{0}C)
Sultaniyethermal springs domed bath	41.10
Sultaniyethermal springs small bath	40.90
Sultaniye drinking water lower part	37.00
Delibeygirmesi	37.50
Rızaçavuşgirmesi (mud pool+pool)	39.00
Rızaçavuşgirmesi (spring)	34.00
Gelgirme	37.00

In the Köyceğiz geothermal field, the lowermost unit contains a probable Lower Cretaceous sandstone and clayey schist unit. The overlying radiolarite, chert, and clayey sandy limestone units are Campanian-Maestrichtian (Upper Cretaceous) in age. The sequence is defined by Quaternary polychaetes. Magmatic activity is observed in the region at two distinct times: Paleozoic ophiolites and Upper Cretaceous ultrabasic and basalt outflows. The region is generally fractured by N-S, NW-SE, and NE-SW-striking faults. Thrusts and possible thrusts are also present [3].

During the project in the Köyceğiz-Sultaniye geothermal field, on-site measurement and water sampling studies were carried out in the hot water sources in the Sultaniye thermal spring and Delibeygirmesi.

S-1 Hot Spring (Sultaniye Hot Spring, Köyceğiz)

This hot spring is located on the shores of Lake Köyceğiz, approximately 12 km southwest of the Köyceğiz district in southeastern Muğla province. In the area operated as Sultaniye Hot Spring, the hot spring reaches the surface from the bottom of a pool (Figure 6). In this area, on-site measurements and water sampling were conducted in seven different periods to determine the physical and chemical parameters of the hot spring (Table 2). The results of major anion and cation analyses are plotted on hydrogeochemical graphs.

Fig. 3. S-1 hot water spring

Table 2. On-site measurement and analysis results of S-1 hot water spring

	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)	B (mg/l)
S-1	11.09.2021	40.40	7.08	42970	8784.00	441.75	968.40	471.15	14202.50	2527.60	264.00	3.65
	29.10.2021	38.80	7.04	43550	8578.80	428.20	649.00	579.50	15946.80	817.30	347.96	3.25
	16.02.2022	39.70	6.90	43140	8068.00	458.50	666.75	511.25	14521.50	1519.70	384.22	3.25
	19.04.2022	40.10	6.85	42850	7967.20	365.70	604.75	454.25	14259.20	2594.40	212.70	2.65
	07.06.2022	40.60	7.06	42920	9094.00	187.60	274.65	301.70	16769.30	2515.90	534.51	1.80
	07.09.2022	40.20	6.97	43230	8902.50	547.90	757.80	572.90	17570.50	2279.60	366.21	3.65
	21.10.2022	39.70	6.78	42850	9021.50	549.95	768.25	578.50	16173.70	2497.10	103.03	1.98

The surface temperature, pH, and EC values of the hot water were measured in the ranges of 38.80-40.60^{0}C, 6.78-7.08, and 42850-43550µs, respectively. The anion sequence is Na>Ca>Mg>K, and the cation sequence is Cl>SO_4>HCO_3 (Figure 4). The major anion/cation analysis results were transferred to the numerical diagrams of Piper [7], Schoeller [8], and Durov [4] for hydrogeochemical evaluation to determine the water type. The S-1 hot water spring reflects the Na-Cl water type (Figures 5, 6).

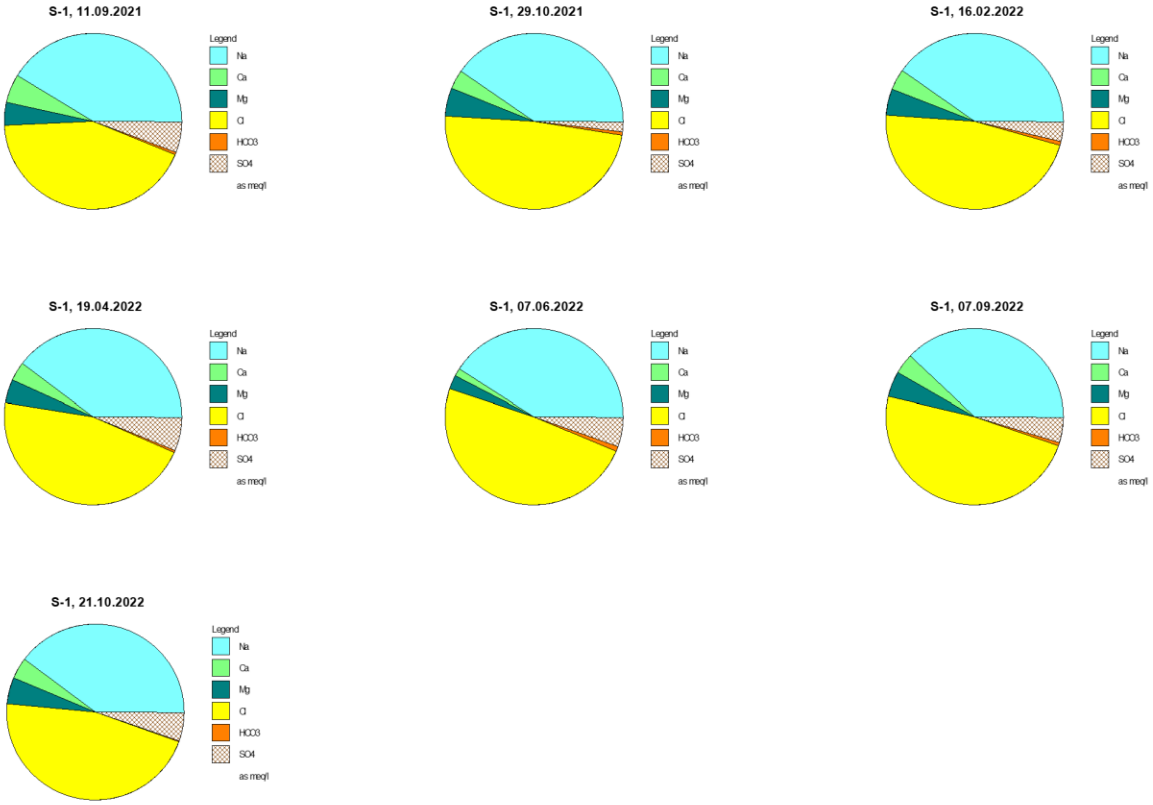

Fig. 4. Pie diagrams showing the major ion distribution in the S-1 hot water spring

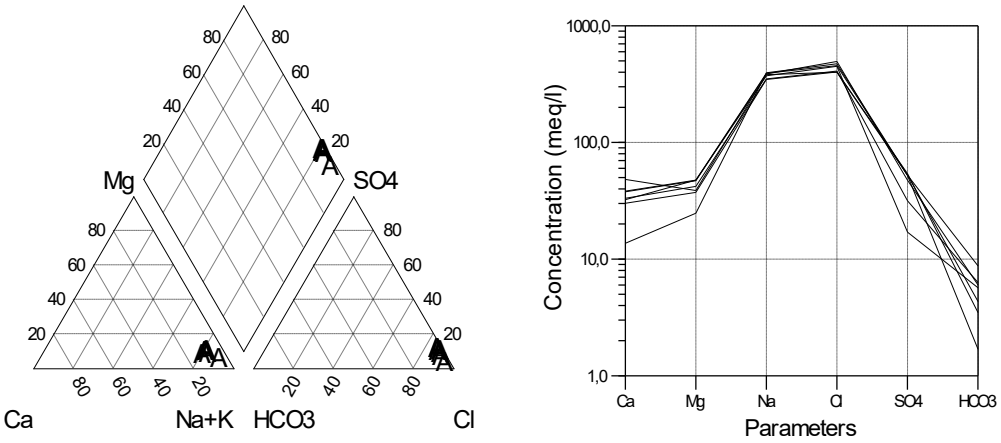

Fig. 5. Piper and Schoeller diagrams prepared based on data from spring S-1

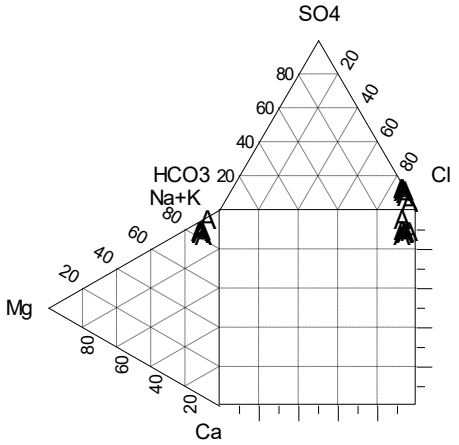

Fig. 6. Durov diagram prepared based on data from spring S-1

The Na-K-Mg triangular diagram is used to determine the origin of geothermal waters, to determine whether they have reached equilibrium, and to select appropriate geothermometers [6]. According to the Na-K-Mg triangular diagram, the S-1 hot spring corresponds to a partially equilibrium water area. These waters are defined as waters mixed with shallow circulating groundwater (Figure 7).

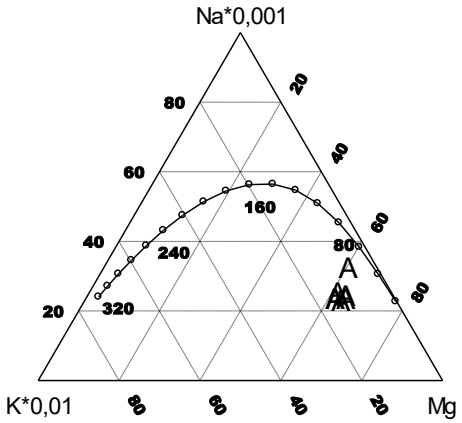

Fig. 7. Equilibrium states in the Na-K-Mg triangle of the S-1 hot water spring

S-2 Hot Spring (DelibeyGirmesi-Köyceğiz)

This hot spring is located approximately 15 km south of the Köyceğiz district in southeastern Muğla province, near Lake Köyceğiz. In the area called DelibeyGirmesi, the hot spring reaches the surface from the bottom of a natural pool (Figure 8). In this area, on-site measurements and water sampling were conducted in seven different periods, and the physical and chemical parameters of the hot spring were determined (Table 3). The results of major anion and cation analyses are plotted on hydrogeochemical graphs.

Fig. 8. S-2 hot water spring

Table 3. On-site measurement and analysis results of S-2 hot water spring

	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)	B (mg/l)
S-2	11.09.2021	38.90	7.26	42880	9018.00	334.00	953.00	700.50	15968.00	2527.00	531.00	1.00
	29.10.2021	36.50	7.03	41840	7831.60	441.05	659.75	499.80	14103.20	1621.45	531.59	3.30
	16.02.2022	27.10	7.25	15450	2693.00	121.35	272.90	208.55	4892.50	899.90	414.47	1.05
	19.04.2022	32.40	7.07	29960	5330.80	285.85	495.60	384.25	9430.50	1703.60	429.29	1.81
	07.06.2022	34.00	7.18	33000	6920.40	160.30	299.65	273.45	12557.50	1885.80	317.17	1.60
	07.09.2022	36.40	7.03	40980	8361.00	479.45	715.35	537.00	15627.70	2401.60	231.88	3.20
	21.10.2022	35.50	6.93	40530	8404.00	493.00	699.80	547.10	16010.60	2313.00	265.70	2.06

The surface temperature, pH, and EC values of the hot water were measured in the range of 27.10-39.90^{0}C, 6.93-7.26, and 15450-42880µs, respectively. The major ion analysis results were plotted on hydrogeochemical graphs. The anion sequence is Na>Ca>Mg>K, and the cation sequence is Cl>SO_4>HCO_3 (Figure 9). The major anion/cation analysis results were plotted on the numerical diagrams of Piper [7], Schoeller [8], and Durov [4] for hydrogeochemical evaluation to determine the water type. The S-2 hot water spring reflects the Na-Cl water type (Figures 10, 11).

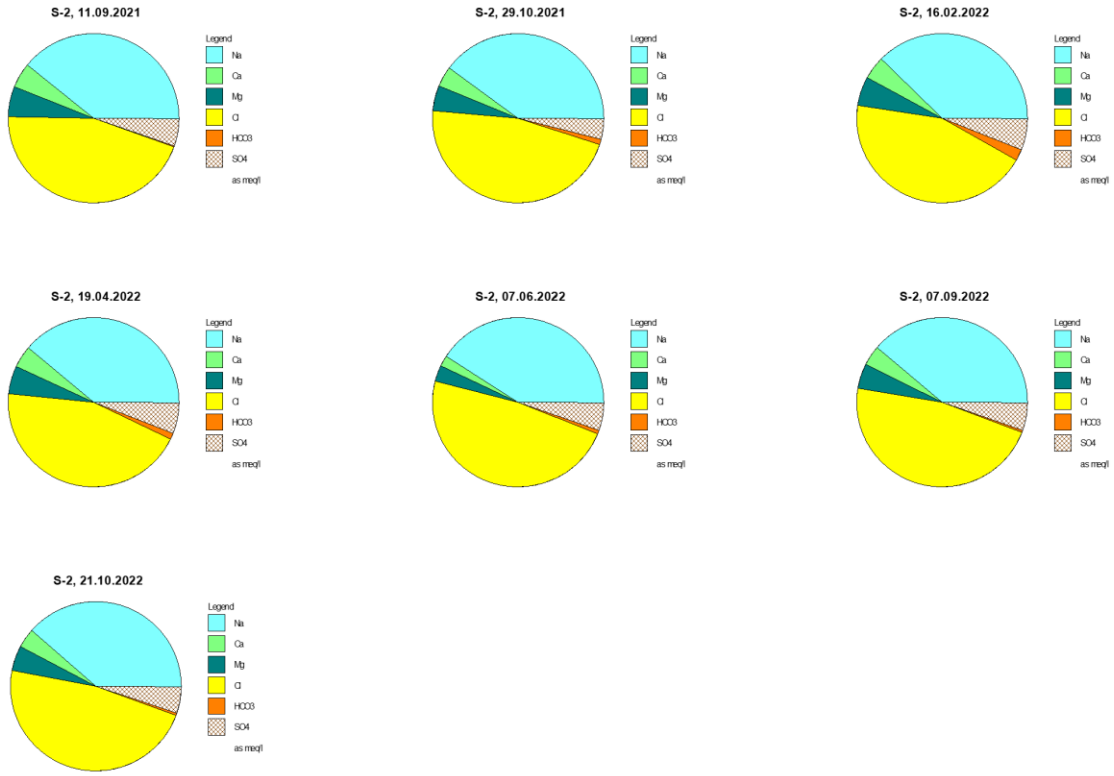

Fig. 9. Pie diagrams showing the major ion distribution in the S-2 hot water spring

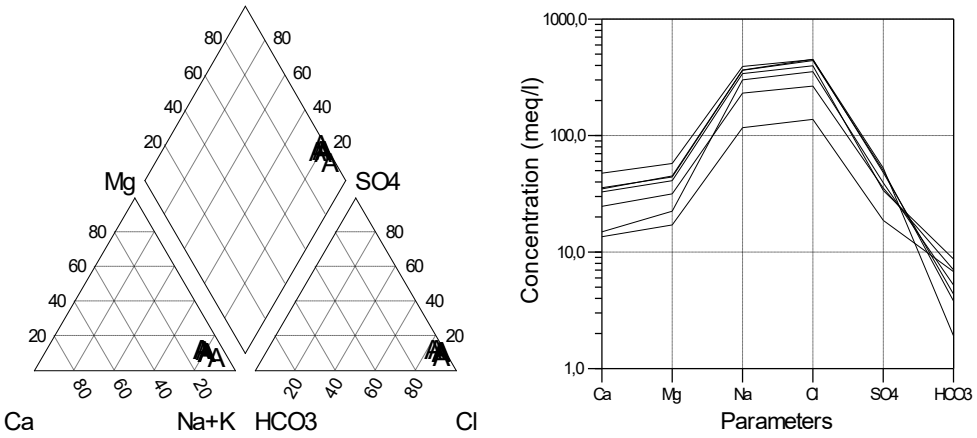

Fig. 10. Piper and Schoeller Diagrams prepared based on data from spring S-2

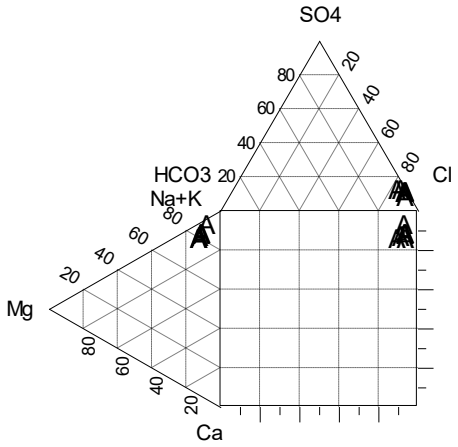

Fig. 11. Durov Diagram prepared based on data from spring S-2

The Na-K-Mg triangular diagram is used to determine the origin of geothermal waters, to determine whether they have reached equilibrium, and to select appropriate geothermometers [6]. According to the Na-K-Mg triangular diagram, the S-2 hot spring corresponds to an area of immature and partially equilibrated waters. These waters are defined as waters mixed with shallow circulating groundwater (Figure 12).

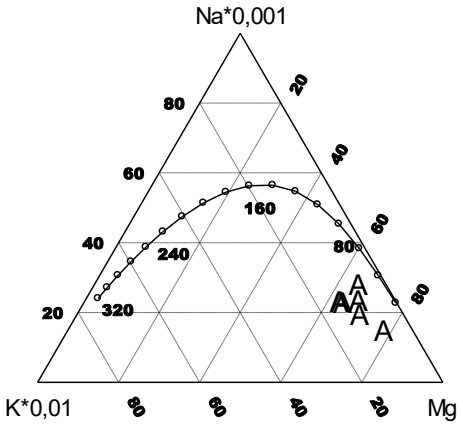

Fig. 12. Equilibrium states in the Na-K-Mg triangle of the S-2 hot water spring

III.1.2. Dalaman Kapukargın (Ortaca-Çürükardı) Geothermal Field

The Dalaman-Kapukargın (Ortaca-Çürükardı) geothermal field is located approximately 7 km southwest of the Dalaman district in the southeastern part of Muğla province. The springs originate from many points in the field and have a very high flow rate (Table 4) [1]. These waters are not being utilized at the spring site. There is no other structure, other than a wooden hut, as a facility. However, in recent years, the Dalaman Municipality has expanded the use of hot waters with a new thermal spring and recreational area project.

Table 4. Resources in the Dalaman-Kapukargın geothermal field [1]

Spring	Temperature (T^0C)
(Kapukargın) Çürükardı	29.00

In the Dalaman-Kapukargın (Ortaca-Çürükardı) geothermal field, the Kayaköy dolomite, composed of Triassic dolomite and dolomitic limestone, lies at the bottom. The Babadağ formation, Orhaniye formation, and Göçgediği formation are located at the top, respectively, of Jurassic age. The Babadağ formation contains cherty limestone and oolitic limestone lenses. The Orhaniye formation consists of cherty micrites with radiolarite intercalations. The Göçgediği formation consists of gray, thin- to medium-bedded chert bands and cherty limestones. The Cretaceous Karaböğürtlen formation, consisting of micrite marl at the base and sandstone, claystone, siltstone, and limestone, lies at the top. This unit is followed by the Paleocene Faralya formation. The formation consists of micritic, turbiditic, generally gray-colored sandy, silty limestone, sandstone, siltstone conglomerate, and greenish sandstone with basic volcanic material. The youngest units in the region are

Quaternary units, consisting of marsh sediments, coastal sand, flood plain sediments, and alluvium. Vertical-slip normal faults are present in the area [2].

During the project in the Dalaman-Kapukargın (Ortaca-Çürükardı) geothermal field, on-site measurement and water sampling studies were carried out from the natural hot water spring on the edge of the DalamanRiver and the natural pool above the thermal spring.

K-1 Hot Spring (Kapukargın Thermal Spring, Dalaman)

Located approximately 7 km southwest of the Dalaman district in southeastern Muğla province, it reaches the surface as a natural spring on the banks of the Dalaman River, on the Dalaman Airport Road (Figure 13). In this area, on-site measurements and water sampling were conducted over seven different periods, and the physical and chemical parameters of the hot spring were determined (Table 5). The results of major anion and cation analyses are plotted on hydrogeochemical graphs.

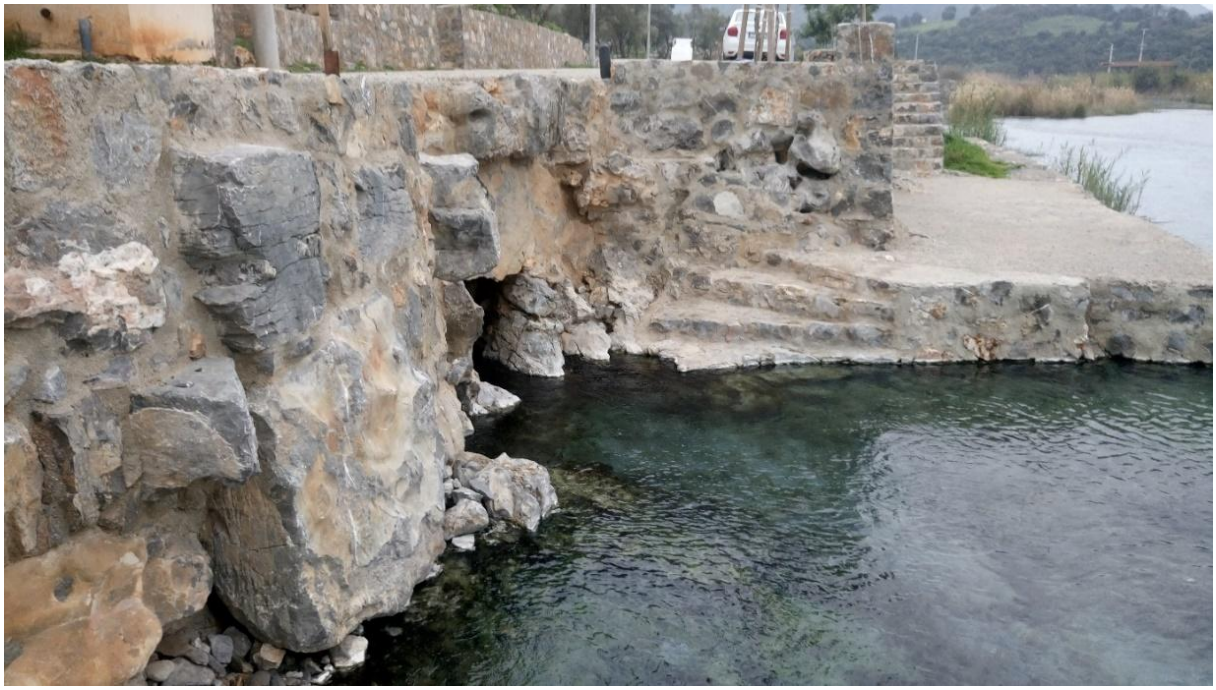

Fig. 13. K-1 hot water spring

Table 5. On-site measurement and analysis results of the K-1 hot water spring

	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)	B (mg/l)
K-1	11.09.2021	31.50	7.32	19350	3021.00	135.25	212.55	237.65	5502.30	840.40	534.02	1.90
	29.10.2021	29.90	7.14	18770	3078.80	142.45	256.75	247.10	5551.90	916.90	368.57	1.32
	16.02.2022	29.90	7.13	18880	3112.00	149.85	223.40	258.85	5325.00	930.30	58.51	1.35
	19.04.2022	29.70	6.99	19680	3139.60	438.60	636.45	499.90	6019.90	903.70	188.87	1.33
	07.06.2022	30.50	7.19	19660	1774.00	186.55	274.45	302.60	7204.00	933.70	629.65	1.75
	07.09.2022	31.20	7.09	18330	1613.20	160.50	286.80	177.10	6395.70	905.20	592.75	1.22
	21.10.2022	30.00	6.99	18430	1812.00	177.45	319.25	296.65	6573.00	873.80	494.05	1.23

The surface temperature, pH, and EC values of the hot water were measured in the range of 29.70-31.50^{0}C, 6.99-7.32, and 18330-19680µs, respectively. The major ion analysis results were plotted on hydrogeochemical graphs. The anion sequence is Na>Ca>Mg>K, and the cation sequence is Cl>SO_4>HCO_3 (Figure 14). The major anion/cation analysis results were plotted on the numerical diagrams of Piper [7], Schoeller [8], and Durov [4] for hydrogeochemical evaluation to determine the water type. The K-1 hot water spring reflects the Na-Cl water type (Figures 15, 16).

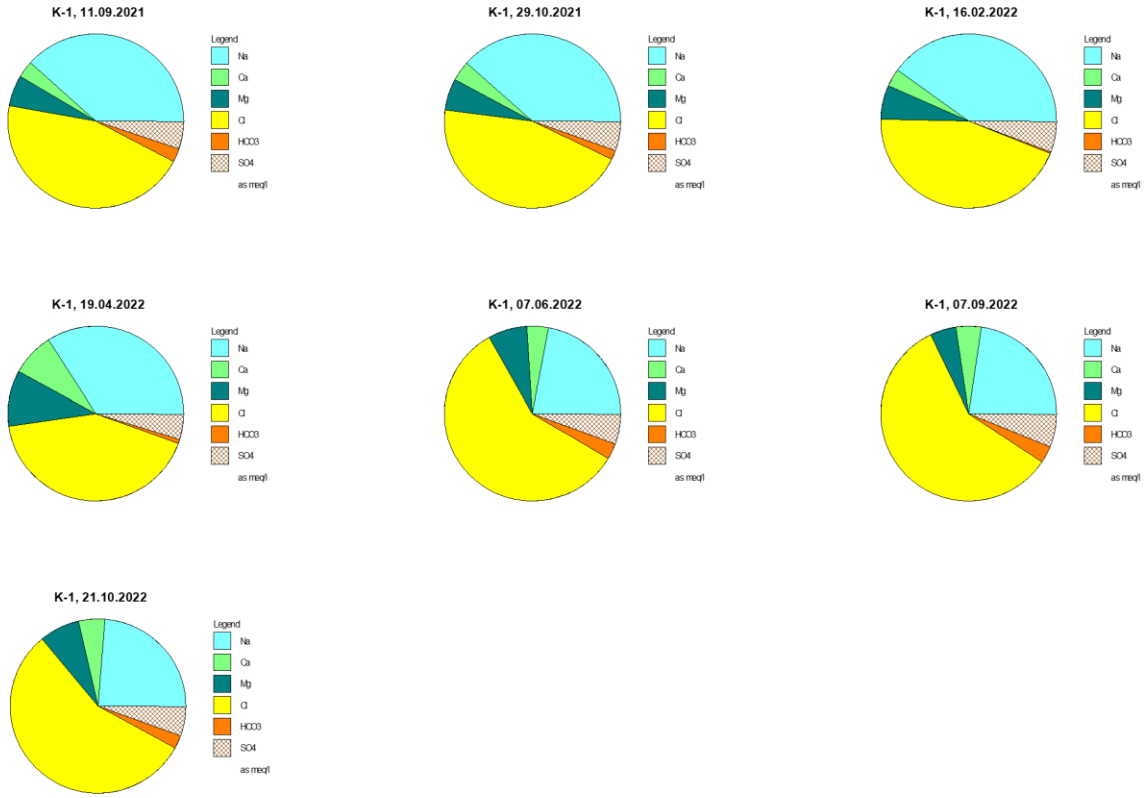

Fig. 14. Pie diagrams showing the major ion distribution in the K-1 hot water spring

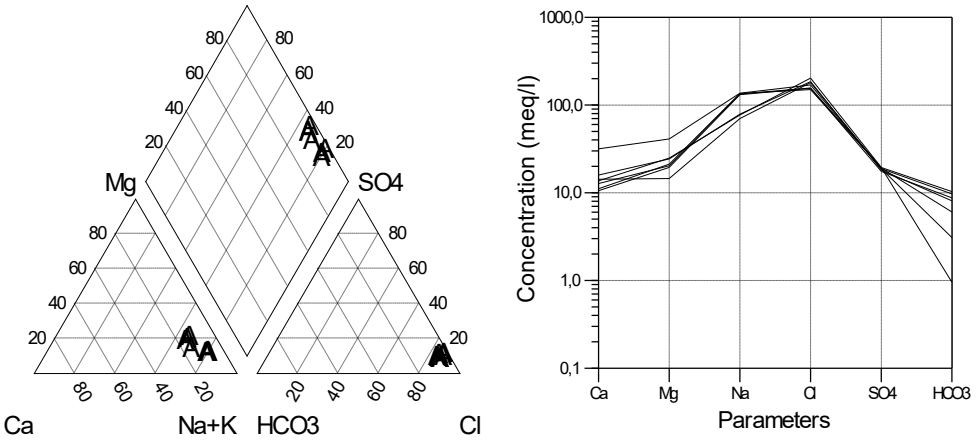

Fig. 15. Piper and Schoeller Diagrams prepared based on data from spring K-1

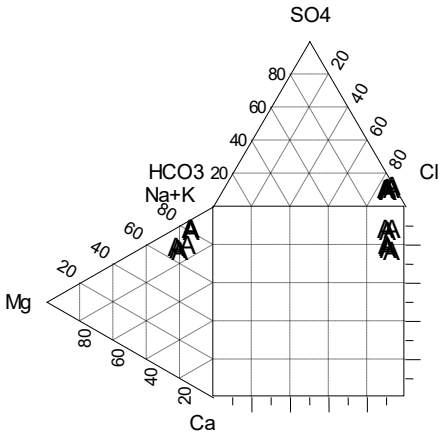

Fig. 16. Durov Diagram prepared based on data from spring K-1

The Na-K-Mg triangular diagram is used to determine the origin of geothermal waters, to determine whether they have reached equilibrium, and to select appropriate geothermometers [6]. According to the Na-K-Mg triangular diagram, the K-1 hot spring corresponds to an area of immature and partially equilibrated waters. These waters are defined as waters mixed with shallow circulating groundwater (Figure 17).

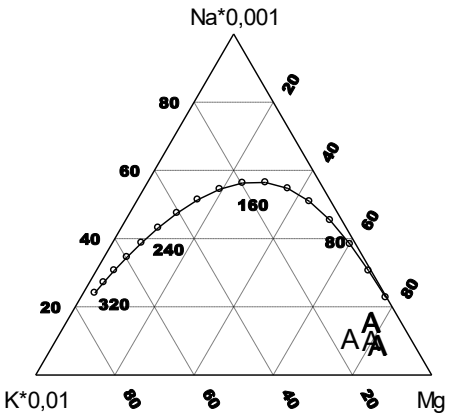

Fig. 17. Equilibrium states in the Na-K-Mg triangle of the K-1 hot water spring.

K-2 Hot Spring (Kapukargın Thermal Pool, Dalaman)

Located approximately 7 km southwest of Dalaman district in southeastern Muğla province, the hot spring reaches the surface from the bottom of a pool just above the Dalaman River on the Dalaman Airport Road (Figure 18). In this area, on-site measurements and water sampling were conducted in seven different periods, and the physical and chemical parameters of the hot spring were determined (Table 6). The results of major anion and cation analyses are plotted on hydrogeochemical graphs.

Fig. 18. K-2 hot water spring

Table 6. On-site measurement and analysis results of the K-2 hot water spring

	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)	B (mg/l)
K-2	11.09.2021	31.90	7.33	18110	3098.40	140.65	232.25	240.85	5523.60	811.20	245.17	1.19
	29.10.2021	30.50	7.16	18090	2949.60	133.45	239.65	235.65	5431.40	811.20	497.01	1.31
	16.02.2022	29.90	7.13	17620	3024.20	145.85	271.60	247.05	5225.80	874.10	152.92	1.27
	19.04.2022	30.20	7.04	17800	2817.20	131.45	252.65	235.75	5346.30	853.70	717.98	1.26
	07.06.2022	31.30	7.20	17670	1771.80	537.35	750.20	565.35	6211.40	863.00	118.87	1.57
	07.09.2022	30.70	7.11	17870	1790.40	161.90	339.40	277.80	6154.60	874.10	433.85	1.21
	21.10.2022	29.80	7.01	17710	1688.80	172.40	379.65	290.05	6090.80	863.50	428.82	1.14

The surface temperature, pH, and EC values of the hot water were measured in the range of 29.80-31.90^{0}C, 7.01-7.33, and 17620-18110µs, respectively. The major ion analysis results were plotted on hydrogeochemical graphs. The anion sequence is Na>Ca>Mg>K, and the cation sequence is Cl>SO_4>HCO_3 (Figure 19). The major anion/cation analysis results were plotted on the numerical diagrams of Piper [7], Schoeller [8], and Durov [4] for hydrogeochemical evaluation to determine the water type. The K-2 hot water spring reflects the Na-Cl water type (Figures 20, 21).

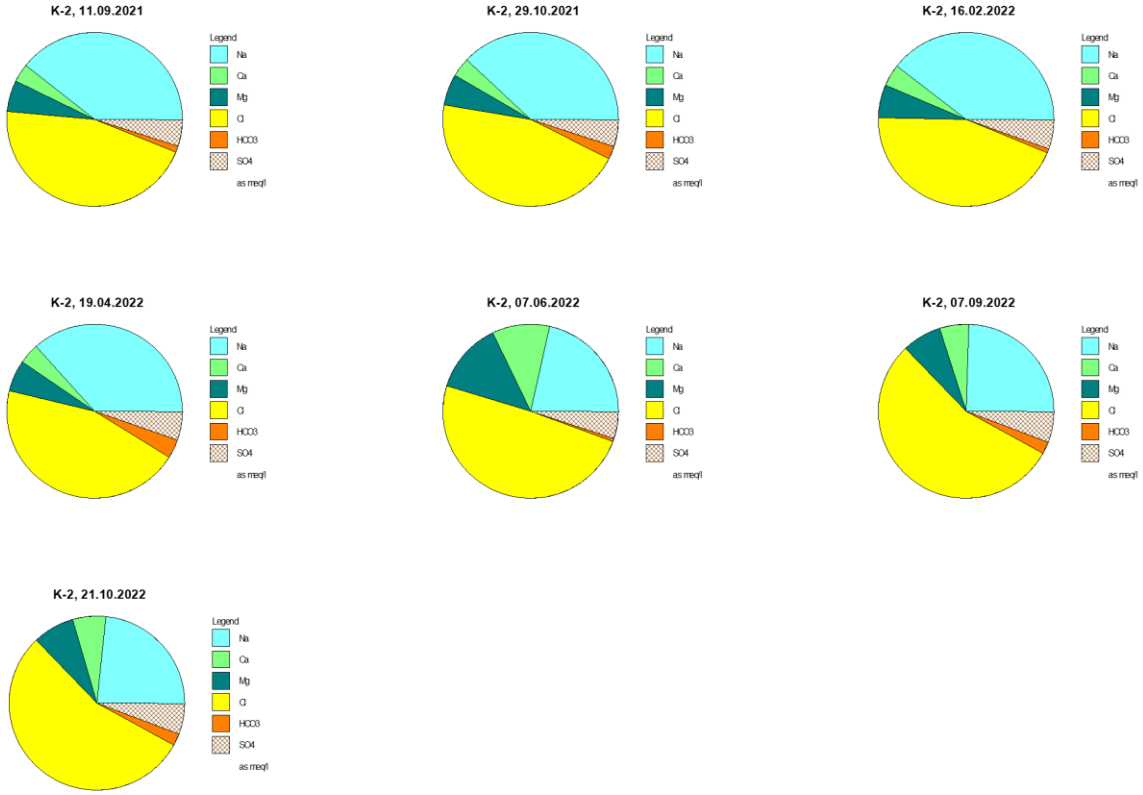

Fig. 19. Pie diagrams showing the major ion distribution in the K-2 hot water spring

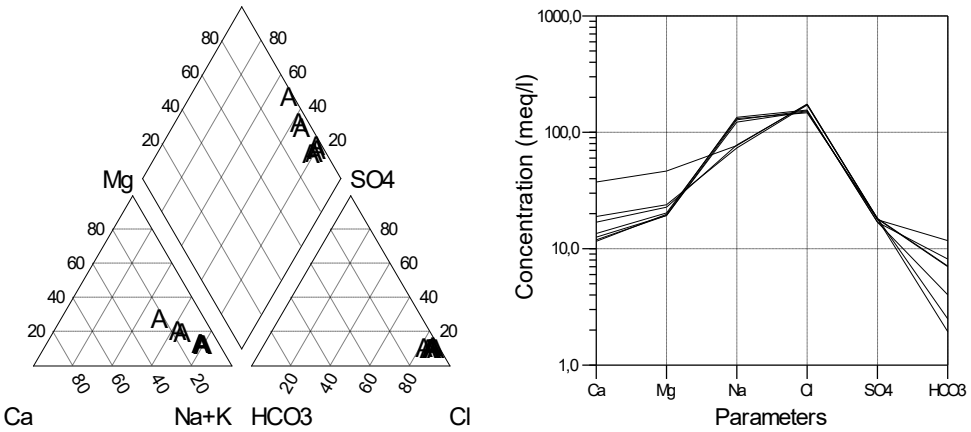

Fig. 20. Piper and Schoeller Diagrams prepared based on data from the K-2 spring

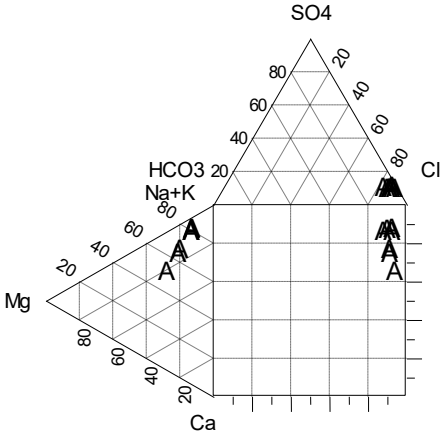

Fig. 21. Durov Diagram prepared based on data from K-2 spring

The Na-K-Mg triangular diagram is used to determine the origin of geothermal waters, to determine whether they have reached equilibrium, and to select appropriate geothermometers [6]. According to the Na-K-Mg triangular diagram, the K-2 hot spring falls within the immature water area. These waters are defined as water mixed with shallow circulating groundwater (Figure 22).

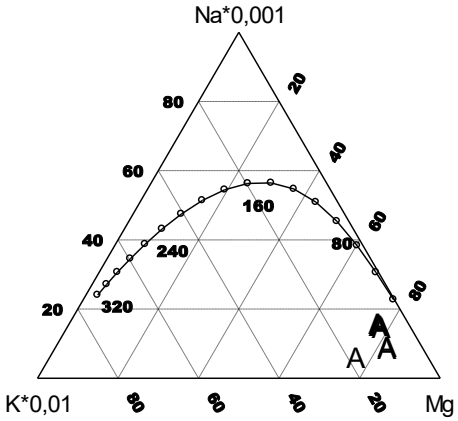

Fig. 22. Equilibrium states in the Na-K-Mg triangle of the K-2 hot water spring

IV. RESULTS

In this study, the hydrogeochemical properties of some geothermal fields in the southeastern part of Muğla Province in SW Anatolia were determined. On-site measurements and water sampling (for hydrochemical analyses) were conducted regularly every two months at the hot springs identified in the geothermal fields.

The area located in and around Muğla province - Yatağan (Bozhöyük), Bodrum (Karaada), Datça (Ilıca, Gölbaşı), Köyceğiz (Sultaniye), Dalyan (DelibeyGirmesi, RızaçavuşGirmesi, Gelgirme), Sarıgerme (Çürükardı) and Fethiye (Gebeler) - contains geothermal fields. The region is quite active in terms of earthquakes in the instrumental period. In this study, regular on-site measurements and sampling studies were carried out at certain periodic times from four hot springs identified in the region between September 2021 and October 2022. These hot springs are the Sultaniye thermal spring (S-1) and DelibeyGirmesi (S-2) in the SultaniyeGeothermal Field in Köyceğiz district, and the Kaynak (K-1) and Havuz (K-2) in the KapukargınGeothermal Field in Dalaman district. On-site measurement and sampling studies were conducted at these hot springs in seven different periods (September 2021, October 2021, February 2022, April 2022, June 2022, September 2022, and October 2022). The water types determined as a result of the hydrogeochemical analyses were determined to reflect the Na-Cl type water for the hot springs in all geothermal areas.

The surface temperature, pH and EC values of the S-1 hot water spring were measured in the range of 38.80-40.60^{0}C, 6.78-7.08 and 42850-43550µs, respectively. The anion sequence is Na>Ca>Mg>K and the cation sequence is Cl>SO_4>HCO_3. The surface temperature, pH and EC values of the S-2 hot water spring were measured in the range of 27.10-39.90^{0}C, 6.93-7.26 and 15450-42880µs, respectively. The major ion analysis results were plotted on hydrogeochemical graphs. The anion sequence is Na>Ca>Mg>K and the cation sequence

is $Cl>SO_4>HCO_3$. The surface temperature, pH and EC values of the K-1 hot spring were measured in the range of 29.70-31.50^{0}C, 6.99-7.32 and 18330-19680µs, respectively. Major ion analysis results were plotted on hydrogeochemical graphs. The anion sequence is Na>Ca>Mg>K and the cation sequence is $Cl> SO_4>HCO_3$. The surface temperature, pH and EC values of the K-2 hot spring were measured in the range of 29.80-31.90^{0}C, 7.01-7.33 and 17620-18110µs, respectively. Major ion analysis results were plotted on hydrogeochemical graphs. The anion sequence is Na>Ca>Mg>K and the cation sequence is $Cl>SO_4>HCO_3$.

According to the Na-K-Mg triangle diagrams, S-1 hot water spring is in partial equilibrium, S-2 hot water spring is immature and in partial equilibrium, K-1 hot water spring is immature and in partial equilibrium, and K-2 hot water spring is in immature water area.

ACKNOWLEDGMENTS

This study was conducted within the scope of ÇOMÜ-BAP-FBA-2021-3679 project of the Scientific Research Projects Coordination Unit of ÇanakkaleOnsekiz Mart University. We would like to thank the ÇOMÜ-BAP Coordination Unit for their financial support.

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