Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Hydrogeochemical Assessment of the Bergama Thermal Waters, İzmir, Turkey

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Keywords: Hydrogeochemistry, Hydrogeology, thermal springs, environmental problems, geothermometers, mineral saturation, Bergama, İzmir, Turkey

ABSTRACT

Bergama is a touristic and historical city belonging to İzmir province, Western Anatolia, Turkey. Thermal waters in Bergama (ancient Pergamon) have been used for the purposes of bathing, therapy and spa facilities for ancient times tracing back Roman Period. In this study, geothermometry applications, mineral equilibriums, hydrogeological and hydrogeochemical properties of thermal waters in the Bergama geothermal fields are described by new data obtained from water points. These geothermal fields are geographically divided into four main groups; Güzellik Spa, Pasha Spa (ancient Allionai), Mahmudiye Spa and Dübek Place wells geothermal fields. Güzellik and Pasha Spas are located in Pergamon and Allionai ancient cities. Bergama and aforementioned geothermal fields are located in the Bakırçay graben, which is one of the western Anatolian grabens. Neogene volcanic rocks known as Yuntdağ volcanics I-II-III, of which components are andesitic components, are widely spreaded in the study area. The Yuntdağ volcanics-I form the aquifer of the geothermal systems in the area. Thermal waters also issue from these volcanic rocks through the intersection of faults. Alteration clays of the Yuntdağ volcanics-II may act as secondary cap rocks of the geothermal systems. Heat source is also high geothermal gradient due to the combination effect of the tectonic and volcanic activities.

The thermal waters of Bergama vicinity have outlet temperatures of 25°C–58°C and EC values of 350-2320 μS/cm. Dominant cations are Na in all the thermal waters. Dominant anions for thermal springs are mostly HCO_3 except for Dübek wells that are SO_4. Chemical equilibrium modeling shows that the thermal waters are mostly oversaturated in aragonite, calcite, dolomite, and undersaturated in gypsum, anhydrite. Chemical geothermometers suggest average reservoir temperatures between 60°C–80°C. As well as these waters are used for balneological and touristic purposes, they should also be used for district and greenhouse heating. One important environmental problem in the study area is high arsenic contents of thermal waters produced from some wells near the Güzellik spa have been used for drinking purposes after cooling. So, thermal waters shouldn't be used for the purposes of drinking and drinking cure. Another important environmental problem is that Pasha Spa waters, which are located in the famous archeological heritage Allionai, will remain under the reservoir waters of the planned Yortanlı Dam.

1. INTRODUCTION

The study area is located in the Bakırçay graben, which is one of the Western Anatolia graben structures (Figure 1). **PERGAMUM** (also spelled **PERGAMON**) was an important capital city in ancient times. The modern city of **BERGAMA** is the successor of ancient **PERGAMUM**. Bergama is home to two of the country's most celebrated archaeological sites: the Acropolis and the Asklepion of the ancient Pergamum both listed among the top 100 historical sites on the Mediterranean. Most of the extraordinary buildings and monuments in Bergama date to the time of Eumenes II (197-159 BC). The ancient city is composed of three main parts: the **ACROPOLIS**, whose main function was social and cultural as much as it was sacred; the **LOWER CITY**, realm of the lower classes; and the Asklepion one of the earliest medical centers on record. Another ancient city Allianoi (modern name is Pasha Spa) is appropriate for 18 km northwest with Bergama. It is famous with the antique therapeutic bath city.

Earlier geothermal exploration studies of Bergama vicinity were evaluated with the neighbor town Dikili vicinity as "Dikili-Bergama geothermal areas" till now (Yılmazer, 1984, Yılmazer and Özgüler, 1986; MTA-JICA, 1987; Filiz et al., 2000). Bergama thermal waters were taken into consideration secondary and less important due to the fact that Dikili thermal waters have higher temperature and discharge quantities (Özen and Tarcan, 2001; Özen et al., 2005). Bergama city has become the largest industrial, agricultural and touristic place in Bakırçay graben, with a population of about sixty thousand. Residential heating in this city and surrounding settlings supplied by coal firing (mostly lignite) that causes environmental problems such as air pollution. The city is today facing environmental problems caused by the expanding industry and their rapidly increasing population. One alternative for residential heating in the city center and nearby little villages is the utilization of geothermal energy. Geothermal energy is environmentally friendly and cheaper than any other heat source for district heating. The district heating applications of some residences of Bergama by using geothermal waters have just been started by Bergama Municipality. Greenhouse heating, balneology applications, thermal tourism and heating of swimming pools are the other uses, which can be developed for this area.

The aim of this study is to discuss the hydrogeological properties and the geochemical characteristics of the thermal waters in the Bergama vicinity. Special emphasizes are put on the studies of water geochemistry, geothermometry, mineral saturations and environmental effects. The semi-arid climate of the study area is characterized by hot dry summers and warm wet winters. The mean annual temperature is 16°C and the total annual rainfall is 636 mm. Thermal waters of the area were collected from natural springs and thermal wells at outlet conditions in September 2003. Two samples from each site were stored in polyethylene bottles. One was acidified with HNO_3 to determine metal contents and the other was unacidified for anion analyses.

Outlet temperature, pH, and electric conductivity were measured in the field. Anion constituents were analyzed in the Dokuz Eylül University Geochemistry Laboratory,

under the supervision of the authors, with standard methods described in Apha (1989). Cl and alkalinity (CO_3 and HCO_3) were determined by titration with silver nitrate and hydrochloric acid, respectively. SO_4 was determined by visible spectrophotometer with barium ions. Na, K, Ca, Mg, SiO_2, B, Li, Al, Fe, As, Cu, Br, Ba, P, Mn and Zn concentrations were analyzed in ACME Analytical Laboratory (Canada) with inductively coupled plasma mass spectrometry. All the analytical results were used to comment on hydrogeology and geochemistry.

2. GEOLOGICAL AND HYDROGEOLOGICAL SETTINGS

The geological map of the study area was simplified from MTA (2002). The oldest units of the Bergama vicinity consist of Permian Çamoba and Lower Triassic Kınık formations. The stratigraphic sequences continue Eocene to Oligocene Kozak granodiorite, Middle Miocene Yuntdağ volcanics-I and II, Upper Miocene Yeniköy formation and Upper Miocene to Pliocene Yuntdağ volcanics-III (Akyürek and Soysal, 1978). Quaternary alluvium is the youngest unit of the area.

Permian Çamoba formation is composed of neritic sediments that are sandstone, siltstone and silty limestone. Lower Triassic Kınık formation is made up of conglomerate, sandstone, siltstone, mudstone, clayey limestone and marine limestone. Kozak granodiorite is comprised plutonic rocks cutting Çamoba and Kınık formations. The Yuntdağ volcanics were divided into three groups: Yuntdağ volcanics-I (Tyu1), Yuntdağ volcanics-II (Tyu2) and Yuntdağ volcanics-III (Tyu3) (MTA-JICA, 1987). The oldest Yuntdağ volcanics-I consists of widely altered andesite. Tertiary Yuntdağ volcanics-II mainly made up of felsic pyroclastics cover the Yuntdağ volcanics-I. This unit consists of dark compact basalt and pyroxene andesite lava including a few small hydrothermal veins. This unit is covered with the youngest Yuntdağ volcanics-III (Tyu3). This rocks that consist of biotite hornblend andesite are occurred dome shaped volcano type. These three volcanic units, which are shortly called as Yuntdağ volcanics, are not been differentiated for this study in the simplified geological map (Figure 1). Upper Miocene Yeniköy formation is made up of lacustrine sediments that are conglomerate, sandstone and claystone. The formation unconformable overlies the Kınık formation and Yuntdağ volcanics- I, II are overlain by unconformable Yuntdağ volcanics-III. The Quaternary alluvium, which is made up of unconsolidated granular sediments, covers all the units. The structural geological setting of the Bergama vicinity on the basis of directions is characterized by the NW-SE trending graben controlled by NW-SE faults.

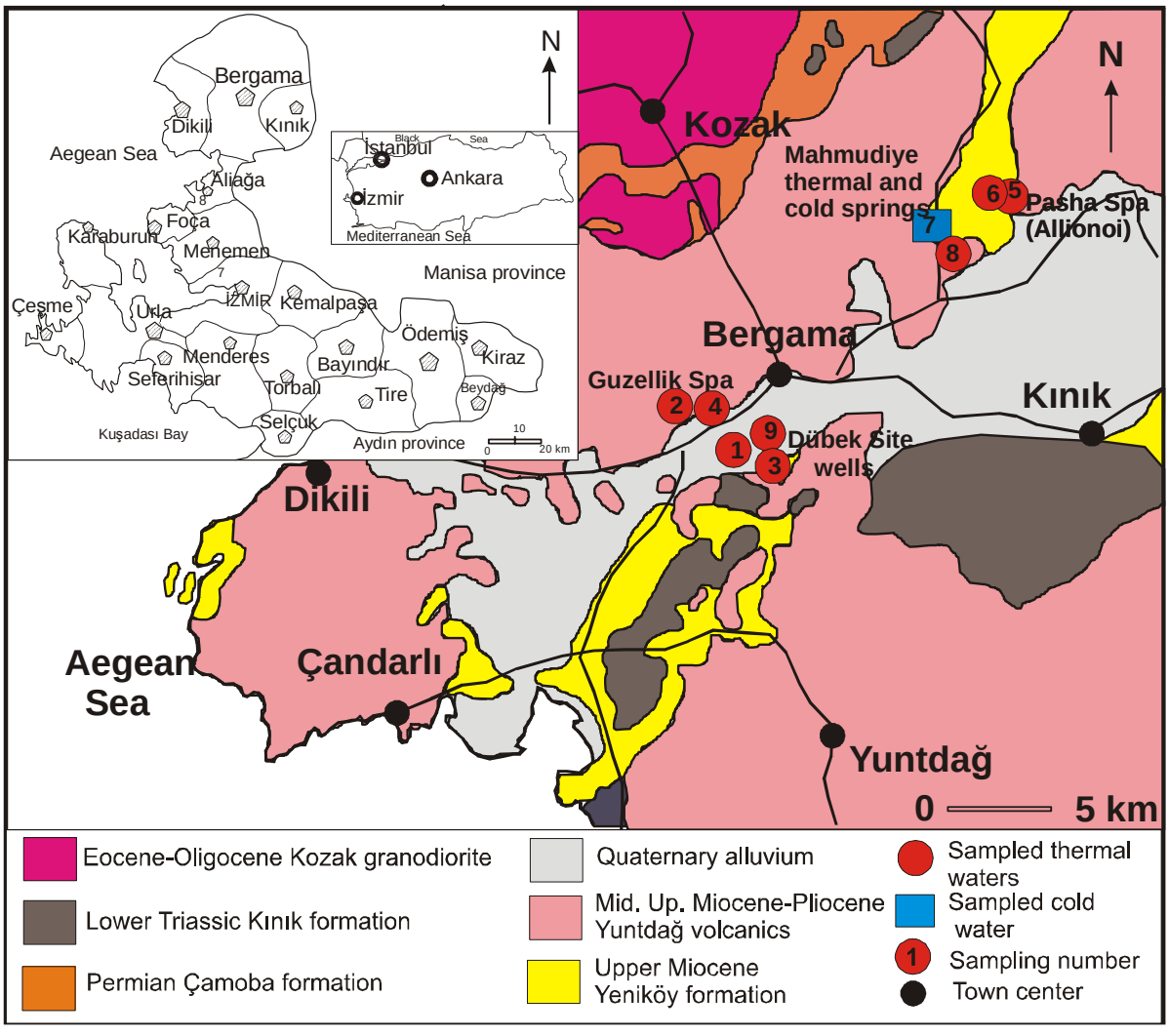


Figure 1: Simplified geological map of Bergama vicinity and locations of the geothermal fields and sampled water points (Geological map is modified from MTA, 2002).

The permeability within the basement rocks (Çamoba and Kınık formations) is highly variable. The limestones are fractured and karstified and act as locally aquifer for cold ground waters. So do the parts of the fractured sandstones. However clayey levels of these units have relatively low permeability. So they act as impermeable basement for the geothermal systems of the Bergama. The Yuntdağ volcanics-I form the reservoir rocks of the geothermal systems of the area. The Yuntdağ volcanics-II including poorly cemented pyroclastics has relatively low permeability due to the altered clayey levels as a whole and may act as cap rocks for the geothermal systems of Bergama. The solidified magma closed to the surface due to the combination of the tectonic and young volcanic activities (maybe Yuntdağ volcanics-III) form the heat source of the geothermal systems. The Paleocene aged granodioritic pluto, which is located to the north of the study area, is too old to be a heat source. Clayey levels of the Upper Miocene Yeniköy formation occur as impermeable barrier rocks. Alluvium is the most important and favorable unit for cold ground water production. It is possible to lift ground water with 5-25 L/s discharges from 20-150 meters deep wells. Ground water flows are towards Southwest. There are already many wells drilled by private companies in this unit.

According to their locations the thermal waters in the Bergama geothermal areas have been physically divided into four groups: Güzellik Spa, Dübek place, Mahmudiye spring and Pasha Spa thermal waters (Figure 1). Güzellik Spa (Güzellik means beauty) thermal spring also known in the past as Dabaklar, is the famous historical thermal spring just like Bergama city where it is in. The waters of this thermal spring got dry because of the uncontrolled excessive ground water pumping from wells that are in the surrounding area. Thermal waters emerged from shallow well (sample 2) with 29^{o}C in this Spa were used as therapeutic, balneologic and swimming pools right now. There are lots of pensions, hotels and settlement sites nearby areas of this spa. GI-1 well (sample 4) with 800 meters deep was drilled 200 meters away from Güzellik spa. Isotopic data reflect the meteoric origin waters with deep circulation and older than 50 years (Filiz et al., 2000; Tarcan et al., 2006). Additionally lots of thermal waters were used for these hotels and sites. Some site houses have been used thermal waters as potable water.

The thermal waters from Dübek place are supplied from wells whose their temperatures attaining 60^{o}C. The waters from sample 1 (DB-1) in this site have been used for the fishery farming heating. The waters from sample 3 (Petrol station well) have been used for potable water. Also the waters from sample 9 have been drilled in this field and used for potable water.

The thermal waters from Pasha Spa (samples 5 and 6) with the temperature 46^{o}C had been used as primitive spa facilities in the past. This spa is also located on the ancient city Allionoi. The waters from this spa have been used for the therapeutic purposes for ancient times. There are lots of historical aqueducts and ruins in this site. This area is the important antique city instead of being thermal site. However this area and thermal springs are located on the Yortanlı River and a dam has been constructed on this river. After the construction of this dam, Allionai antique city and Pasha Spa thermal baths will be under the waters of the dam lake near future. This dam building will be harmful not only famous antique city, but also thermal waters of the area. So, this should be dealt with an environmental problem for the region. Mahmudiye thermal spring (sample 8) is issued from the border of Yuntdağ volcanics and Yeniköy formations. It has very low salinity and used for spa facilities. The cold spring locating on this field (sample 7) is also issued from limestones of Yeniköy formation. This cold spring is used for drinking and irrigation purposes.

3. WATER GEOCHEMISTRY

The results of chemical analyses of the waters sampled for this study are shown in Table 1 and Table 2. Table 1 also includes the classification of waters made on the principles of the IAH (1979). Total equivalents of cations and anions were taken as 100% and ions with more than 20% (meq/l) were used for the classification. Although six different thermal water types are identified, the major cation is Na for all the hot water and major anion is mostly HCO_3 and partly Cl and SO_4. The thermal waters have temperatures between 25 and 58^{o}C with electrical conductivity values of about 350-2320 µS/cm. The chemistry of cold waters is mainly dominated by Ca and HCO_3 ions. Main components of the waters are plotted on the triangular diagrams (Figure 2 and Figure 3).

Table 1: Water points and some physicochemical properties of the Bergama geothermal fields, Turkey, Sample numbers are the same as in Figure 1.

No	Names of Water Points	Location	T(^{o}C)	pH	EC µS/cm)	TDS (mg/l)	Total Fr. Hardness	% SAR	Water Type
1	DB-1 (O.doğu fishery well	Dübek	58	7,55	1443	1154,8	3,2	26,4	Na-Cl-SO4-HCO3
2	Güzellik Spa well	Güzellik	29	8,22	1592	940,4	2,0	38,9	Na-HCO3-Cl-SO4
3	Shell station well	Dübek	27	7,83	804	417,1	14,1	4,9	Na-Ca-HCO3-Cl
4	GI-1(Güzellik Spa-1well)	Güzellik	36	7,53	1574	924,3	3,4	29,2	Na-HCO3-SO4
5	Pasha Spa hot pot	Pasha	46	6,52	2320	1122,3	15,7	20,8	Na-HCO3
6	Pasha Spa main hot spring	Pasha	46	6,56	2270	990,4	14,6	20,5	Na-HCO3
7	Mahmudiye cold spring	Mahmudiye	19	7,36	428	290,8	17,5	0,5	Ca-HCO3
8	Mahmudiye hot spring	Mahmudiye	31	8,88	350	197,1	2,1	8,1	Na-HCO3-SO4
9	DB-2 well (300 m)	Dübek	25	8,12	1400	995,7	4,2	25,2	Na-SO4-HCO3

Table 2: Chemical analyses of waters from the Bergama geothermal fields, Turkey. Sample numbers are the same as in Figure 1 and Table 1. All concentrations are in mg/L. Blanks refer no records and concentration limits.

No	1	2	3	4	5	6	7	8	9	MAC (TS-266)
Na	344	399	135	392	598	570	14,8	84,9	374,2	200
K	3,7	8,6	4	3,6	16,7	20,2	1,4	0,6	3,9	
Ca	10,52	4,967	41,38	10,52	45,38	41,8	61,13	6,551	13,66	200
Mg	1,4	1,82	9,136	1,9	10,6	10,1	5,5	1,14	1,89	50
Cl	327	201	75	35	105	105	12	9	30	250
SO_4	379,8	237,4	9	386	295	195	32,9	55,1	471	250
HCO_3	400,2	622,2	336,7	503	1523	1506	222	192,8	405	
CO_3		31,7		9,6				22	8	
SiO_2	66,75	66,33	48,69	71,21	33,98	32,3	59,74	30,44	76,38	
B	0,511	0,787	0,152	0,549	4,703	4,21	0,056	0,05	0,461	1,0
Li	0,157	0,071	0,069	0,152	0,398	0,37	0,004	0,004	0,184	
As	0,071	0,227	0,031	0,087	0,965	0,69	0,003	0,022	0,078	0,010
Sr	0,608	0,14	0,6	0,609	1,001	0,93	0,393	0,043	0,758	
Fe	0,035	0,01	0,015	0,973	0,069	0,07	< 0,001	0,022	0,135	0,200
Al	0,023	0,014	0,013	0,223	0,01	0,01	0,017	0,028	0,015	0,200
Ba	0,042	0,023	0,088	0,025	0,112	0,11	0,123	0,01	0,037	1,0
Br	0,085	0,103	0,079	0,085	0,116	0,11	0,036	0,045	0,099	
Mn	0,065	0,019	0,315	0,037	0,048	0,05	0,001	0,002	0,033	0,050
P	< 0,02	0,025	0,078	0,031	0,036	0,03	0,278	0,033	< 0,02	
Zn	0,022	0,011	0,032	0,01	0,006	0,004	0,013	0,005	0,005	5,0
Cu	0,01	0,004	0,002	0,008	0,005	0,01	0,001	0,001	0,005	2,0

MAC (TS-266): Maximum admissible concentrations according to the Turkish Drinking Standards (TS-266, 1999 and 2005)

3.1 Hydrogeochemical Outline

Figure 2 shows that all the thermal waters are located at the Na+K corner except sample 7 (cold spring), which is located in the Ca corner.

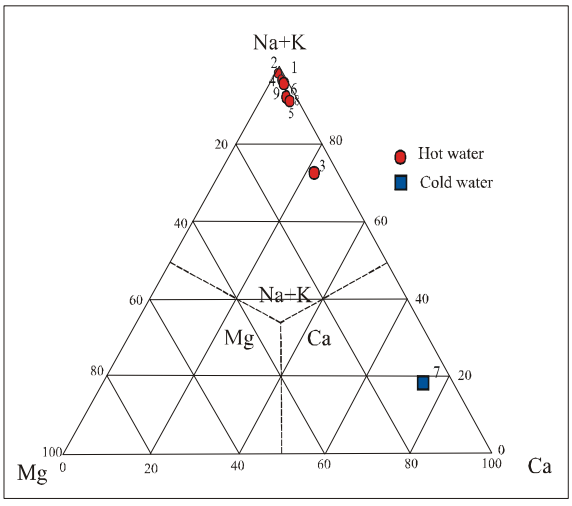


Figure 2: The Na+K-Ca-Mg diagram for the waters in Bergama vicinity on ppm. Sample numbers are the same as in Table 1 corresponding to the locality numbers shown in Figure 1.

In the trilinear Cl-SO_4-HCO_3 diagram (Giggenbach, 1988 and 1991), data points for waters from the Bergama vicinity plot in the HCO_3 field except for the sample no 9 (DB-2 well) that plot in the SO_4 field (Figure 3). Datum point sample 1 (DB-1 well) plots on the border of the HCO_3 and SO_4 fields. They are peripheral waters. The high HCO_3 and very low Cl contents indicate the meteoric origin of the waters as proved by isotopic data (Filiz, 1982; Jeckelman, 1998; Filiz et al., 2000; Tarcan et al., 2006). Na-HCO_3 type thermal waters are produced by rock dissolution and ion exchange reactions in deep aquifers (Tarcan et al., 2005; Tarcan and Gemici, 2005). Although the expected type of thermal waters in the geothermal aquifers is initially Na-HCO_3, mixing during the upflow, and re-equilibration processes cause Na-HCO_3 type waters to turn into various types as shown in Table 1. The dominant anion of waters is mostly HCO_3 attaining 1523 mg/L.

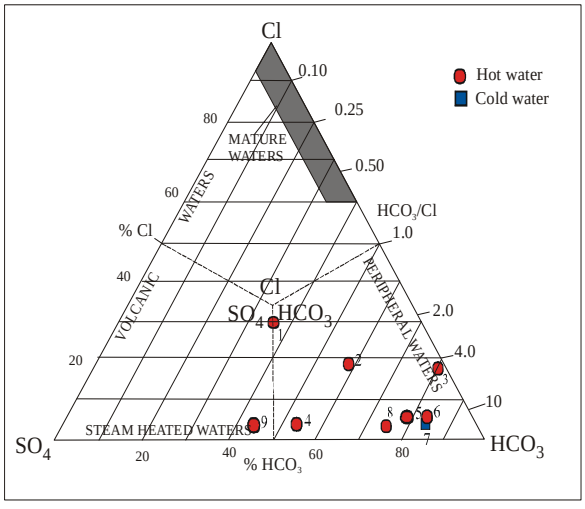


Figure 3: The Cl-HCO_3-SO_4 diagram for the waters in the Bergama vicinty on ppm. Sample numbers are the same as in Table 1 corresponding to the locality numbers shown in Figure 1.

The triangular diagram in Figure 4 shows the relative contents of B, Li and Cl of the thermal waters from the Bergama vicinity. Since Li is one of the alkali metals that are least affected by secondary processes, it may be used as

a tracer for the initial deep rock dissolution processes to evaluate the possible origin of the other two important conservation constituents of thermal waters, Cl and B (Giggenbach, 1991). As seen in the Figure 4, Bergama waters (the samples 1, 2, 3, 7, 8) plot in the Cl area, near the Cl corner indicating absorption of the low B/Cl steam. Sample 7 is cold spring. The others are Dübek, Güzellik and Mahmudiye thermal waters. This water type could be considered as relatively older geothermal systems. The samples 4, 9, 5 and 6 plot the middle sections of the diagram. This kind of waters indicates medium B/Cl steam.

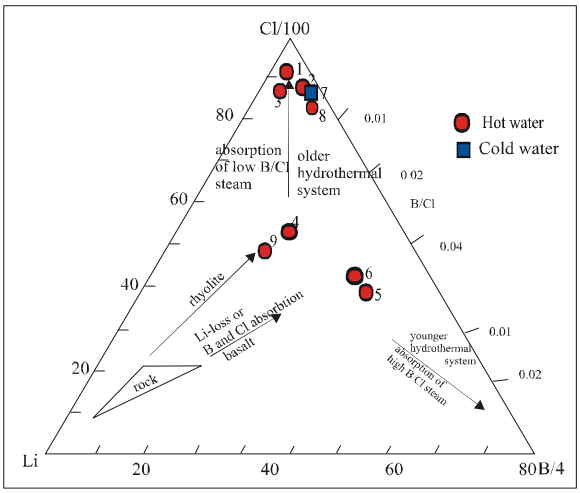


Figure 4: The Cl-Li-B diagram for the waters in the Bergama vicinity on ppm. Sample numbers are the same as in Table 1.

The relations of the constituents in water samples from the geothermal areas in Bergama vicinity are presented in Figure 5. The concentrations of these ions were plotted against each others that are regarded as the chemically conservative for thermal waters from the study area. The correlation coefficients (r) between Cl with B, SiO_2, HCO_3, and Li for waters from the study area are 0.11, 0.20, 0.15 and 0.37 that indicate very poor fit. On the contrary, the correlation of coefficients of B with Li and HCO_3 are 0.93 and 0.99, respectively. These indicate very good fit. Similarly, the correlation coefficients between As and HCO_3, and As and Li ions for waters from the study area are 0.96 and 0.82 that indicate positive good linear relationships. The close positive linear correlation between Li, As, B, HCO_3 and some of the other ions (Figure 5) corroborates that geochemical processes for thermal waters are combination effects of the dissolution of carbonates and silicates and the mixing phenomenon and ion exchange reactions.

Thermal waters from Bergama are suitable for district heating, greenhouse heating, swimming pool, bathing and balneological purposes. But the chemical analyses (Table 2) revealed that the concentrations of As (for all thermal samples), Na (most of the thermal waters exceptional with samples 3 and 8) and B for Pasha spa thermal waters (samples 5 and 6) exceed the Turkish drinking water limits (TS-266, 1997 and 2005). Na contents slightly exceed the drinking standards. But As contents of the thermal waters of the Bergama vicinity are very remarkable reaching 965 ppb. The waters of Pasha Spa (samples 5 and 6) springs have the highest As contents among the others. This can cause environmental problems for ground and surface waters and soils in the study area. As discussed before thermal waters produced from some uncontrolled wells in and around Güzellik spa and Dübek sites have been used for potable waters. This is very dangerous for human healthy. So thermal waters in Bergama vicinity should not been used for any drinking purposes.

3.2. Geothermometer Applications

Various chemical geothermometers were used to estimate the reservoir temperature of the thermal waters in Bergama vicinity (Table 3). Some results of the geothermometers seen in Table 3 are meaningless since they are lower than the measured outlet temperatures or minus value. Discarding these data, the rest of the data can be used to estimate the reservoir temperature. The assessments of the geothermometry results suggest the reservoir temperatures of Bergama geothermal fields can be between 60°C–80°C. The ternary plot of Na/1000-K/100-$Mg^{0.5}$ proposed by Giggenbach (1988) for this study is illustrated in Figure 6. The samples 1, 2, 4 and 9 fall into the field "partially equilibrated waters" and Pasha Spa waters (samples 5 and 6) fall into the border of the immature and partially equilibrated fields. This combining geothermometer diagram shows that the reservoir temperatures of the Bergama geothermal systems vary between 60°C-120°C. The samples 3, 7 and 8 fall into the field "immature waters field indicating none of these waters have attained equilibrium with their associated host rocks as it is expected.

3.3 Mineral Saturation

Mineral equilibrium calculations are important to predict which minerals may precipitate during the extraction and use of the waters. A saturation index of zero indicates that thermodynamic equilibrium exists with the solid phase of relevant mineral. A negative (–) or a positive (+) index indicates undersaturation and oversaturation, respectively. Mineral saturation indices of hydrothermal minerals, which are possible to present in the reservoirs of the geothermal systems, were calculated at outlet temperature and pH by PhreeqCi computer code (Parkhurst and Appelo, 1999). Chemical equilibrium modelling shows that all the waters are undersaturated with respect to anhydrite, gypsum and celestite at all the temperatures. The other minerals are oversaturated or undersaturated at different temperatures. Calcite, aragonite, dolomite minerals are mostly oversaturated at different temperature ranges. During the extraction and using stages of thermal waters in Bergama vicinity, precipitation of carbonate minerals (calcite, aragonite and dolomite) may be the most critical scaling problem.

Saturation indices can be used as geothermometers by plotting of temperature versus Saturation Index (SI) diagrams. Reed and Spycher (1984) proposed that if the SI with respect to several minerals converges to zero at a particular temperature, this temperature corresponds to the most likely mineral solution equilibrium temperature or at least the equilibrium temperature of that particular water. Figure 7 shows the SI with respect to selected hydrothermal minerals versus temperature for the thermal waters of the Bergama vicinity geothermal areas. Saturation indices were initially calculated by using the PhreeqCi computer code (Parkhurst and Appelo, 1999) at outlet temperature and measured pH. Temperature was then changed iteratively and the saturation indices recomputed. Saturation indices for each mineral were then plotted versus temperature and trend curves depicted.

For DB-1 well (sample 1) SIs with respect to calcite and chalcedony converge exactly zero at ~80°C and SIs of the other selected minerals converges above the zero line at ~90°C; the different minerals also approach zero at different temperatures. The waters from Güzellik spa and Petrol

station well (samples 2 and 3) do not show equilibrium at any temperature. For the Pasha Spa springs (sample 5 and 6) the SIs with respect to the calcite, dolomite, chalcedony and gibbsite exactly approach zero at ~60°C. For the GI-I well (sample 26) the SIs with respect to K-feldspat, albite and calcite and quartz converges onto the zero line at ~65°C and dolomite and chalcedony minerals converges onto the equilibrium line at ~90°C. This can indicate the contributions of two different temperature fluids.

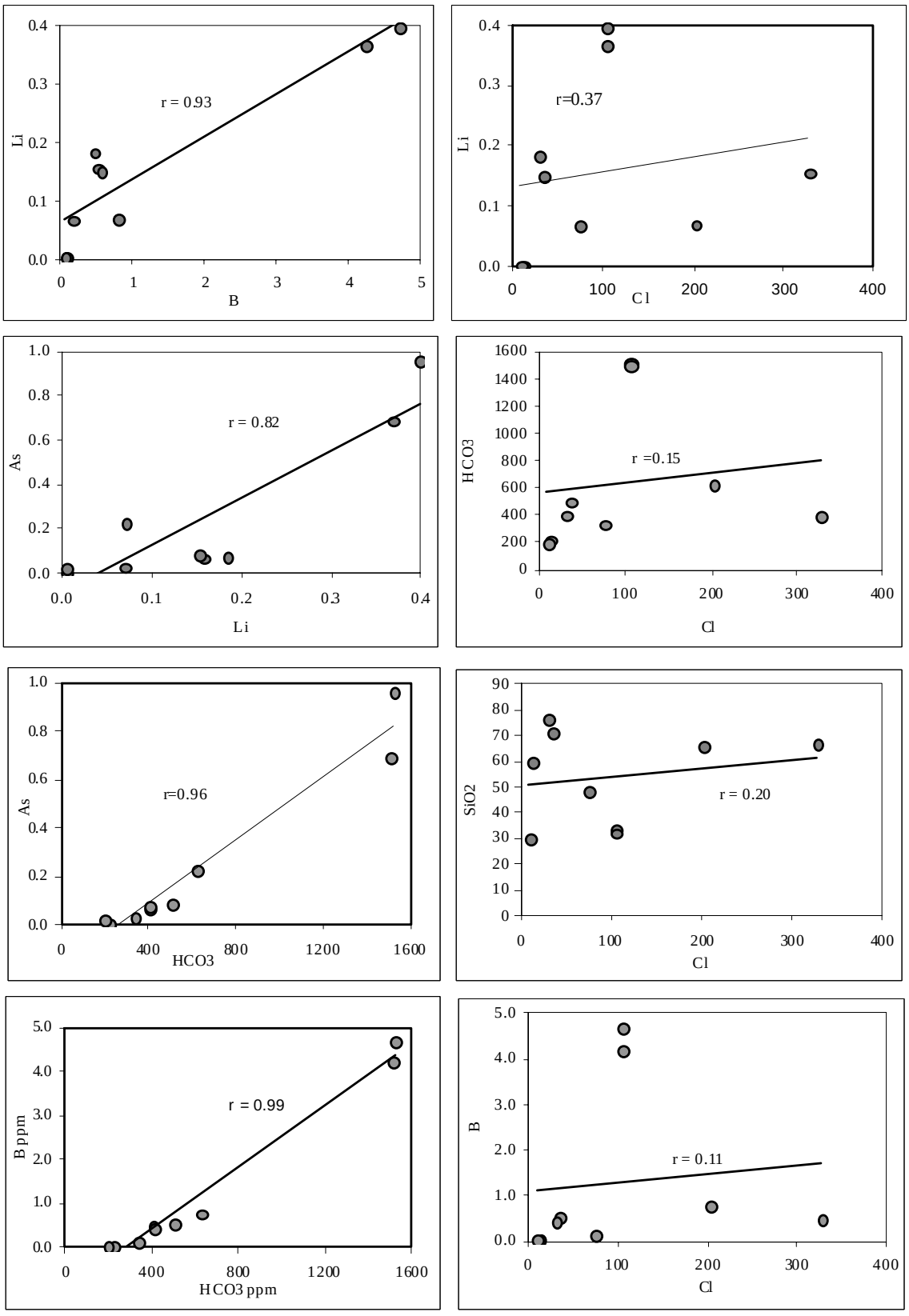


Figure 5: Relations between various ions for thermal waters from the Bergama vicinity, Turkey (values are in mg/L and r is correlation coefficients for linear regression between major ions).

Table 3: Some geothermometry equations and calculated reservoir temperatures of the thermal waters in Bergama geothermal fields, Turkey. Sample numbers are the same as in Figure 1.

No and Name	Geothermometric Equations	1	2	3	4	5	6	8	9
1-SiO_2 Amorp Quartz*	t= 731 / (4.52 - log SiO_2) - 273.15	-6	-6	-19	-3	-32	-34	-36	0
2-SiO_2 Alpha Cristoba.*	t= 1000 / (4.78 - log SiO_2) - 273.15	65	65	50	68	35	33	30	72
3-SiO_2 Beta Cristobalite*	t= 781 / (4.51 - log SiO_2) - 273.15	18	17	3	21	-11	-13	-15	24
4.SiO_2 Chalcedony*	t= 1032 / (4.69 - log SiO_2) - 273.15	87	87	70	90	53	51	49	94
5-SiO_2 Quartz*	t= 1309 / (5.19 - log SiO_2) - 273.15	116	115	101	119	85	82	80	123
6-SiO_2 Quartz(Steamlose)*	t= 1522 / (5.75 - log SiO_2) - 273.15	115	114	101	117	88	86	84	120
7-K/Mg**	t= 4410/(13.95-log K^2/Mg) - 273.15	33	27	50	36	37	35	48	35
8-Li/Mg***	t= 2200/(5.470-log ($Li/Mg^{0.5}$)) - 273.15	69	46	28	64	67	66	-5	70
9-Na/Li****	t= 1590/(0.779+log (Na/Li)) - 273.15	113	78	117	106	129	127	38	116
10-Na/Li Cl<10g +	t= 1000/(0.389+log (Na/Li)) - 273.15	14	-16	18	8	28	27	-49	17
11-Na/Li Cl>10g +	t= 1195/(0.130+log ($Na/Li^{0.5}$)) - 273.15	26	-2	30	21	39	38	-33	29
12-Na/K ++	t= 933/(0.933 + log Na/K) - 273.15	18	55	76	11	72	88	-1	17
13-Na/K+++	t= 1319/(1.699 + log Na/K) - 273.15	30	66	86	23	82	98	11	28
14-Na/K ++	t= 777/(0.70 + log Na/K) - 273.15	87	123	143	79	139	154	68	85
15-Na/K ++	t= 856/(0.857 + log Na/K) - 273.15	79	113	131	73	128	142	62	78
16-Na-K-Ca (mmol) x	t=1647/(logNa/K+βlog√a/Na+2.24)- 273.15	94	131	115	93	133	143	35	91
17-Na-K-Ca-Mg xx	R= (Mg/Mg+Ca+K) x 100		70	68	87	70	70		

*: Fournier, 1977; **: Giggenbach et al., 1983; ***: Kharaka and Mariner, 1989; ****: Kharaka et al., 1982; +: Fouillac and Michard, 1981; ++: Arnórsson et al., 1983; +++: Truesdell, 1976; x: Fournier and Truesdell, 1973; xx: Fournier and Potter, 1979

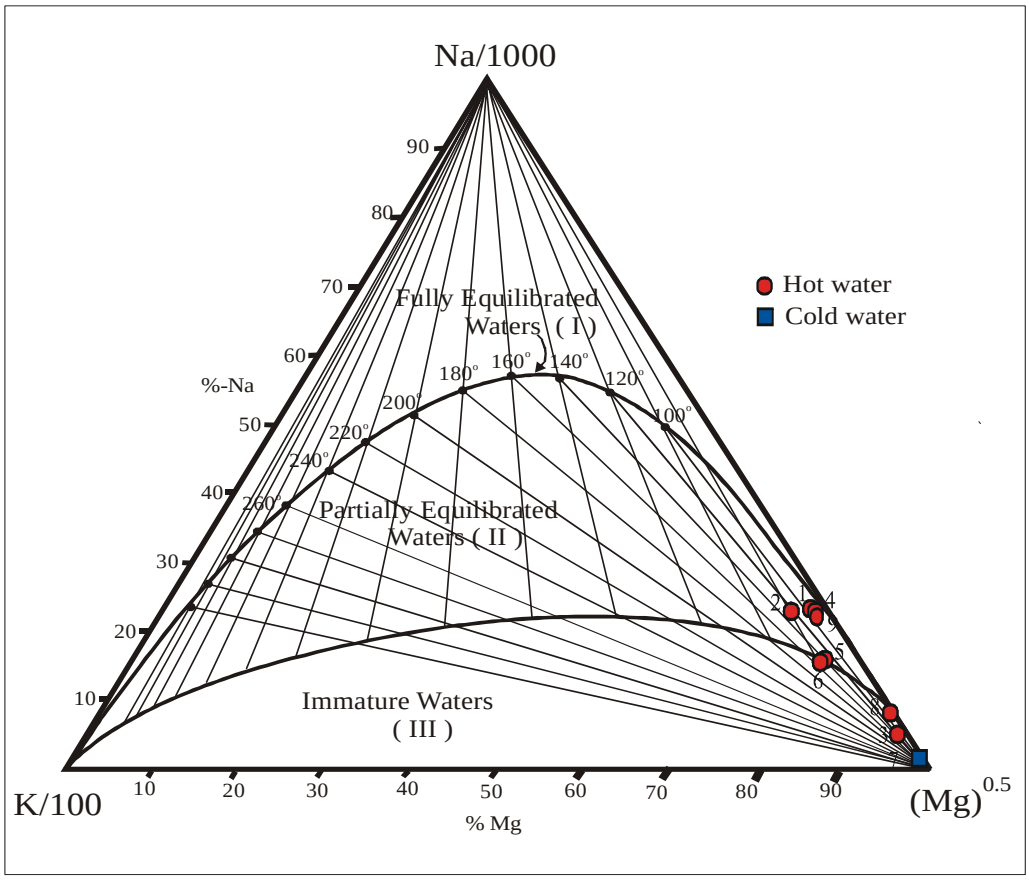


Figure 6: The Na-K-Mg diagram (Giggenbach, 1988) for waters in Bergama vicinity in mg/kg. Sample numbers are the same as in Table 1.

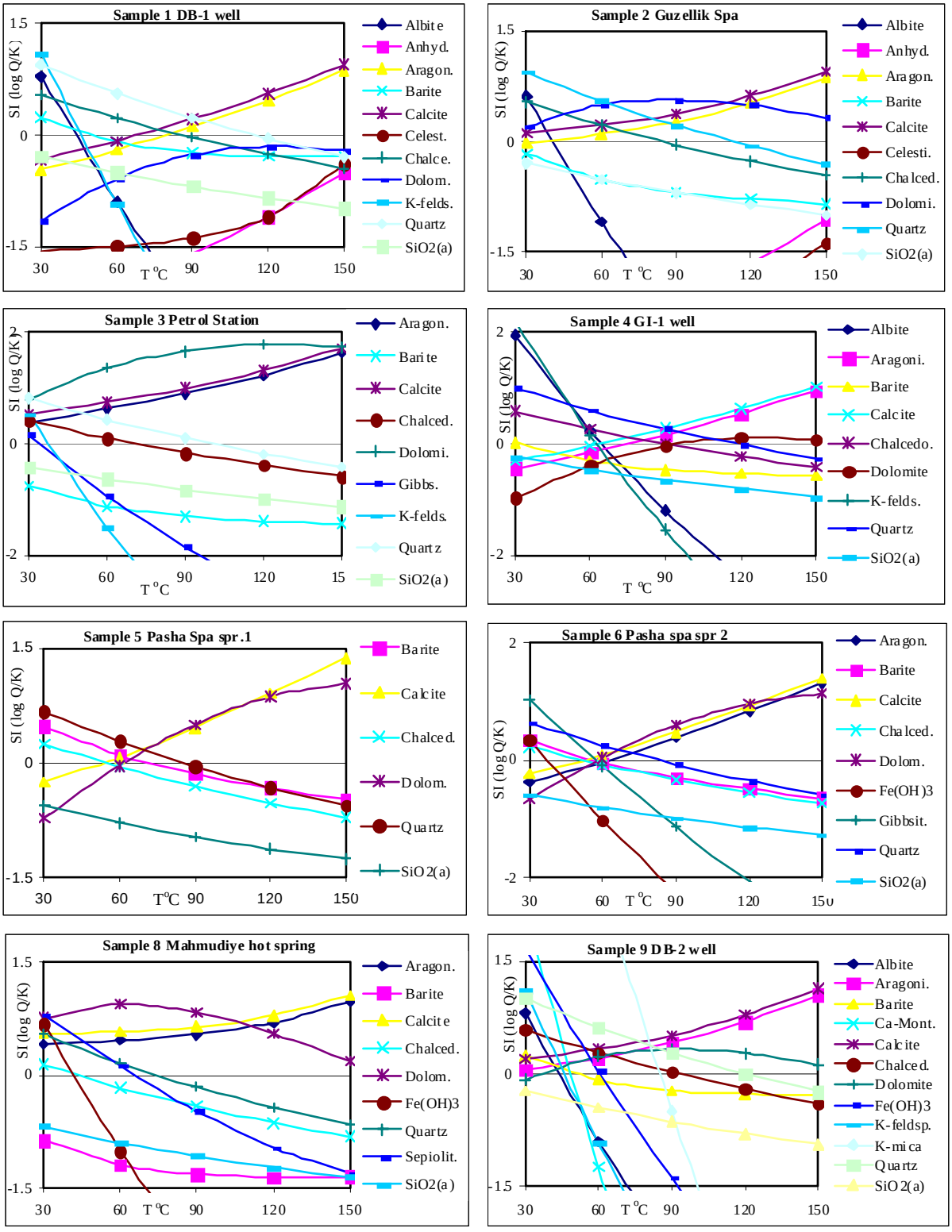


Figure 7: Mineral equilibrium diagrams for thermal waters from the Bergama vicinity, Turkey.

For the Mahmudiye thermal waters (sample 8) Fe(OH)3 and chalcedony are in equilibrium at ~40°C. For the DB-2 well waters (sample 9) SIs with respect to selected minerals approach cross each others above the zero line at ~50°C, ~70°C and ~90°C indicating mixing with different temperature fluids. The crossing of the lines for several minerals below or above the zero may indicate admixtures of waters at various temperatures. These findings suggest that the thermal waters of the Bergama vicinity geothermal areas are partially equilibrated waters feeding by geothermal fluids at different temperatures between 40°C-90°C. The average reservoir temperatures of them are around 60°C.

4. CONCLUSIONS

This study evaluates the hydrogeological and hydrogeochemical properties, chemical geothermometers, environmental impacts and the states of mineral saturation of the thermal waters in Bergama vicinity geothermal fields. Yuntdağ volcanics-I consisting of fractured andesitic rocks

is the reservoir rocks in the Bergama geothermal systems. Since the rocks of Yuntdağ volcanics-II including alteration clayey levels is relatively impermeable, they act as the system cap rock. Heat source of the geothermal systems is probably the geothermal gradient originated from combinational effects of the young volcanic and tectonic activities. The circulation of the thermal waters in the geothermal fields is also closely related to major fault and fracture zones.

The thermal waters of Bergama have been used for bathing and medicinal purposes since the ancient times tracing back Roman Period. Thermal waters in Bergama vicinity are located in four different sites calling as Dübek site wells (25^oC-58^oC), Güzellik spa wells (29^oC-36^oC), Mahmudiye hot spring (31^oC), and Pasha Spa spring (46^oC). Thermal waters have 5 different water types while dominant cation is always Na, dominant anion of them is mostly HCO_3. The combined effects of cation exchange and calcite, dolomite and silicates dissolution can explain the occurrence of these type waters. In the Li, Cl and B triangular diagram, thermal waters plot in the Cl area indicating absorption of the low B/Cl steam.

The thermal waters of Bergama vicinity contain remarkable arsenic concentrations reaching 0,965 mg/L. This can cause environmental problems in aquifers, surface waters and soils in agricultural areas. Additionally these thermal waters produced from uncontrolled wells in some places have been used for drinking purposes after the cooling. This can also cause important healthy problems for local people. So these waters shouldn't be used for any drinking and drinking cure purposes. One more important environmental problem in the area is related to the Pasha Spa thermal waters situated in Allionai ancient city. A dam has been built on the Yortanlı River. Pasha spa thermal springs and famous antique Allionai city will be under the waters of Yortanlı dam lake reservoir area after the finish of the dam buildings.

Chemical equilibrium modeling indicates that carbonate minerals (calcite, aragonite and dolomite) are the most critical scaling problem. The combinational comments on estimated geothermometry and mineral saturation results show the geothermal systems, which have low enthalpy fluids (about 60^oC-80^oC), and hydrogeochemical assessments indicate that thermal waters were fed by fluids having different temperature.

ACKNOWLEDGEMENTS

The authors acknowledge the financial supports of TÜBİTAK Research Fund (Project number: YDABAG 102Y039). Thanks are due to Dr. Niyazi Aksoy for his assistance during the sampling of some waters.

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