Hydrogeological and Isotopic Survey of Geothermal Fields at Buyuk Menderes Graben

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Abstract
The main high and low enthalpy geothermal fields of Buyuk Menderes graben (Western Anatolia) and their reservoir temperatures are as follows; Kizildere (242 ºC), Germencik (232 ºC), Aydin-Ilicabasi (101 ºC), Yılmazkoy (142 ºC), Salavatli (171 ºC), Soke (26 ºC) and in Denizli –Pamukkale (36 ºC), Karahayit (59 ºC), Golemezli (101 ºC) and Yenice (70 ºC). The geothermal system has been controlled by the active graben faults. The reservoir rocks in the geothermal fields are the limestone and conglomerate units in Neogene sediments and marbles-quartzite units in Paleozoic metamorphic formations.

There are clear $\delta^{18}O$ shifts from the Mediterranean Meteoric Water Line (MMWL) in Kizildere, Germencik and Aydin fields. Also, good relation between high temperature and $\delta^{18}O$ shift are observed. It shows deep circulation and water rock interactions. In Pamukkale, Karahayit, Golemezli Yenice fields and Soke region low temperature, small isotope shift, shallow circulation and mixing with shallow cold water are determined.

Keywords
Hydrogeology, isotope, geothermal fields, Buyuk Menderes Graben, Turkey

1. Introduction

Geothermal activity is thought to be enhanced by tensional forces that resulted from the rigid behavior of Western Anatolia during the Neogene, which has caused the formation of extended coastal grabens. The geothermal areas that were identified and explored naturally lie along these grabens mainly the Buyuk Menderes, Gediz, Simav, Bakircay, Izmir, Gonen and Edremit grabens. A total of 123 hot springs were identified and 36 geothermal areas were located [1], [2], [3].

The reservoir and cap rock characteristics which affect the water circulation system and the source and mechanism of heating are still under investigation. Up to now a total of 500 shallow and deep wells have been drilled in the fields (including about 200 shallow gradient wells in the high temperature fields of Kizildere, Seferihisar and Tuzla).

The main purpose of geothermal investigations in Turkey is the development of hydrogeological and geothermal models, determination of the energy capacity, utilization possibilities, and disposal areas for reservoir wastewater (reinjection). However, operation-management and maintenance strategies for an optimum utilization require the knowledge of some important hydrogeochemical interactions and behavior of the reservoir. Considering this fact, the project is designed to determine the relations between chemical properties such as acidity, and origin of fluid production and reinjection at Western Anatolia mainly Buyuk Menderes Graben Geothermal Province which includes Kizildere, Tekkehamam, Germencik, Salavatli, Yılmazkoy, Aydin-Ilicabasi geothermal fields as well as the adjacent fields such as Pamukkale–Karahayit, Golemezli and Yenice (Figure.1). The water of reservoir fluid in Kizildere, Tekkehamam and Germencik is acidic in character.

Recharge mechanism, geochemistry and hydrodynamic structure of the system and effects on hydrothermal systems have to be investigated and explained very carefully in order to utilize the geothermal field at optimum capacity [4], [5], [6]. Without doubt, this will be accomplished by isotope techniques on samples which will be taken from geothermal fluid, a very useful tool in the above mentioned studies in the investigated region [7], [8] [9] [10] [11] [12] [13]. For that reason, sampling points, sampling time and periods chosen accordingly.

Detailed hydrogeochemical studies have been carried out and chemical analyses made in Hacettepe University UKAM laboratories. Analyses of the samples (^{2}H, ^{18}O and ^{3}H) which were collected from thermal and cold water points in the study area have been made in IAEA

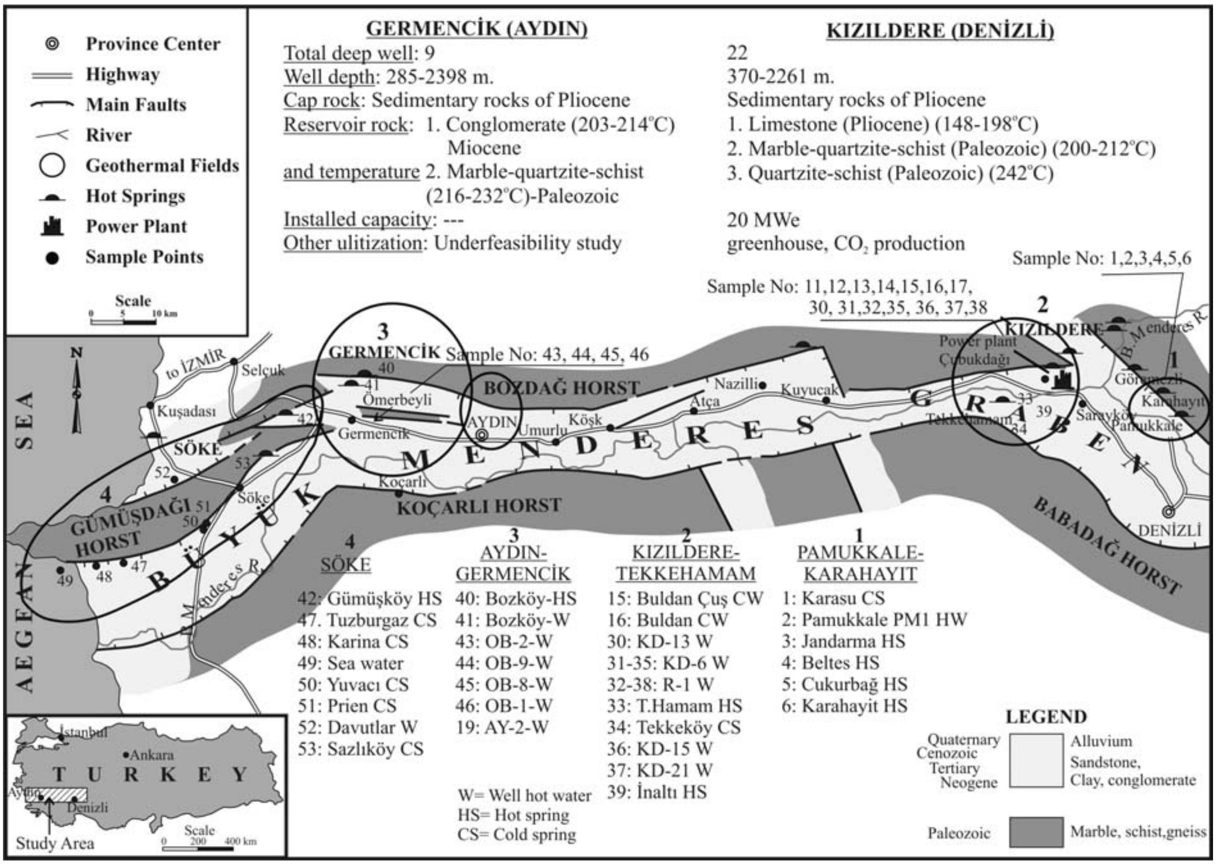

Figure 1. Main geothermal fluids and sampling points of the study area.

4. Results of the Hydrogeological, Chemical and Isotope Survey

Buyuk Menderes Geothermal Province located in the Western Anatolia. Three groups of fields are situated in Project area. These fields are Kizildere, Pamukkale, Aydin and Soke fields (Figure 1). Climate of the area is a typical Mediterranean climate. Winter and spring are the rainy seasons. Average precipitations are 500, 560, 670 and 893 mm/year respectively in 1960-2000 period.

Pamukkale –Karahayit Fields

One of the World Cultural Heritage Site travertine and thermal springs emerging in the Pamukkale area occur in the Çuruksu graben, which belongs to the widespread Buyuk

Menderes Graben system. Two thermal discharging fields in the area are Pamukkale (36 ºC) and Karahayit (59ºC). The main aquifer supplying hot and mineralized water to the Pamukkale thermal springs is the Paleozoic and Mesozoic limestone [14]. The marble is overlain and confined by thick, impervious units of Pliocene age. The catchment area extends along the horst side and consists mainly of Pliocene sediments.

Chemical analysis of thermal spring water shows that the major cations are Ca and Mg, the major anions are HCO_3 and SO_4, and the main water type is calcium bicarbonate (Table 1). The waters are typical of a karstic aquifer, and their chemical composition is almost constant from place to place. The results of ^{13}C analyses show that main source of the CO_2 is the decomposition of marine carbonates [9], which is consistent with an origin in the Mesozoic limestone and Paleozoic marbles. Figure 2 depicts the ^{18}O-D relation for the hot springs of Pamukkale and the adjacent hot springs. The geothermal exchange effect is not observed in the hot waters, which are affected to a great extent by meteoric waters (Table 2). Tritium data show that the hot and mineralized waters are mainly of meteoric origin, with residence time of about 20-30 years.

Table 1. The chemical analysis results of the cold-hot waters of Pamukkale-Karahayit, Denizli-Kizildere, Aydin-Germencik and Soke regions (July, 1998)

Region	Sample No	*Sampling Location	T (°C)	pH	EC (µS/cm)	Na (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	CO_3 (ppm)	HCO_3 (ppm)	Cl (ppm)	SO_4 (ppm)	B (ppm)
PAMUKKALE KARAHAYIT	1	Pamukkale Motel HW	35,00	6,01	2800	27,50	32,50	490,00	87,50	--	1207,80	7,70	728,00	--
	2	Jandarma HS	35,50	6,06	2550	35,00	27,50	470,00	87,50	--	1195,60	17,73	728,03	--
	1995 3	Beltes HS	35,50	6,02	2850	32,50	42,50	477,50	98,00	--	1226,10	7,09	731,44	--
	4	Çukurbağ HS	55,00	6,38	4700	32,50	27,50	600,00	97,50	--	1445,70	31,91	837,36	--
	5	Karahayıt HS	55,00	5,85	3750	50,00	52,50	505,00	120,00	--	1244,40	28,36	922,77	--
	6	Karasu CW	12,00	7,34	260	2,20	2,00	70,00	3,00	--	207,00	14,18	4,81	--
DENIZLI-KIZILDERE	30	KD13 HW	79,50	7,62	11000	1125,00	132,50	20,00	1,00	19,56	2214,48	102,80	637,03	11,75
	31	KD6A HW	83,80	8,18	10000	955,00	132,50	122,50	1,50	32,61	2055,33	102,80	617,91	8,30
	32	R1 HW	76,70	8,18	12500	1595,00	127,50	25,00	1,50	45,66	3222,20	147,12	747,95	19,10
	33	Tekkehamam HS	67,80	7,07	9000	905,00	92,50	45,00	4,50	218,70	820,94	88,62	988,84	9,72
	34	Tekkeköy CS	28,90	8,37	1300	32,50	17,50	125,00	65,00	56,07	302,13	21,27	290,91	1,70
	MRBK	Menderes RW	14,10	8,45	900	51,70	11,00	91,00	46,00	72,90	199,53	63,81	141,15	1,40
	MRAK	Menderes RW	19,10	8,18	1200	72,40	35,00	135,00	70,00	56,07	239,42	67,35	415,21	1,59
AYDIN-GERMENCİK	40A	Aydın	29,00	7,00	3400	978,00	33,00	169,50	49,50	0,00	1821,33	436,03	36,74	16,51
	40B	Bozköy HS	59,50	6,83	10000	1505,00	90,00	90,00	17,50	285,99	1818,59	1152,12	46,30	20,49
	41	Bozköy-Confined HS	55,00	7,30	10000	1320,00	100,00	167,50	67,50	489,12	1611,13	1063,50	3,66	10,85
	42	Gümüsköy HW	38,70	6,96	5000	705,00	62,50	152,50	30,00	56,07	729,74	957,15	37,50	2,99
	43	ÖB2 HW	47,50	6,71	9000	1445,00	135,00	30,00	1,00	0,00	1419,53	1559,80	33,30	31,32
	44	ÖB9 HW	88,60	8,20	14200	1440,00	140,00	85,00	10,00	336,45	860,83	1542,07	43,62	27,83
	45	ÖB8 HW	48,50	7,08	8800	1410,00	122,50	62,50	1,50	0,00	1396,72	1488,90	96,02	29,00
	46	ÖB1 HW	30,00	7,21	6500	1440,00	60,00	50,00	1,00	0,00	1140,21	1595,25	125,85	31,06
SÖKE	47	Tuzburgazi HS	20,60	6,68	39500	9230,00	360,00	640,00	437,50	39,24	267,97	15598,00	1577,87	3,83
	48	Karina HS	26,60	7,03	45000	11725,00	480,00	715,00	462,50	22,44	119,74	19852,00	1858,98	5,12
	49	Sea Water	27,50	8,33	46000	12110,00	485,00	505,00	477,50	56,07	62,71	20029,20	1786,32	5,89
	50	Yuvacı CS	19,50	7,85	2200	360,00	20,00	120,00	47,50	44,85	153,90	638,10	212,51	1,67
	51	Prien CS	21,40	7,54	750	29,00	15,00	93,00	40,00	50,46	267,97	42,54	92,19	1,62
	52	Davutlar HW	41,70	6,28	12000	1650,00	110,00	462,50	80,00	112,14	1185,78	2747,37	58,73	2,22
	53	Sazlıköy HS	26,80	7,56	1130	37,30	7,00	152,00	44,00	112,14	437,86	49,63	22,59	1,74

* :Abbreviations; **HW** (hot water well), **HS** (hot water spring), **CS** (cold water spring), **RW** (river water)

Kizildere Geothermal Field

Kizildere Geothermal Field is located 40 km west of Denizli city. This field was discovered by the cooperative project between MTA-UNDP in 1968. The Kizildere field is situated in the eastern part of the Buyuk Menderes Graben (Figure 1). After the geological, geophysical and geochemical studies, 20 deep wells with a depth changing from 370 m to 1241 m were drilled in the years between 1968-1973. The field has 2 reservoirs; first reservoir (130-198°C) and the second reservoir (200-212 °C) are in production. EUAS (Turkish Electricity Authority) have installed the power plant with 20 MWe capacity in the area in 1984. Also the factory started production of CO_2 in 1986 with a capacity of 120,000 ton/year. In addition, there is application of greenhouse heating (6000 m^2). A feasibility study to the remaining fluid (about 140 MWt) as district heating and industry of Denizli.

Besides of 20 exploration and production wells, the reinjection explanatory well (R-1 and R-2), which is the depth of 2261 m. was drilled by MTA on behalf of EUAS at 1998 and the highest reservoir temperature (242 ºC) in the metamorphic basement (quartzite-schist) has been determined at R-2 in this field, also in Turkey. This third reservoir was assumed to exist in the area by hydrogeological and chemical indications [15].

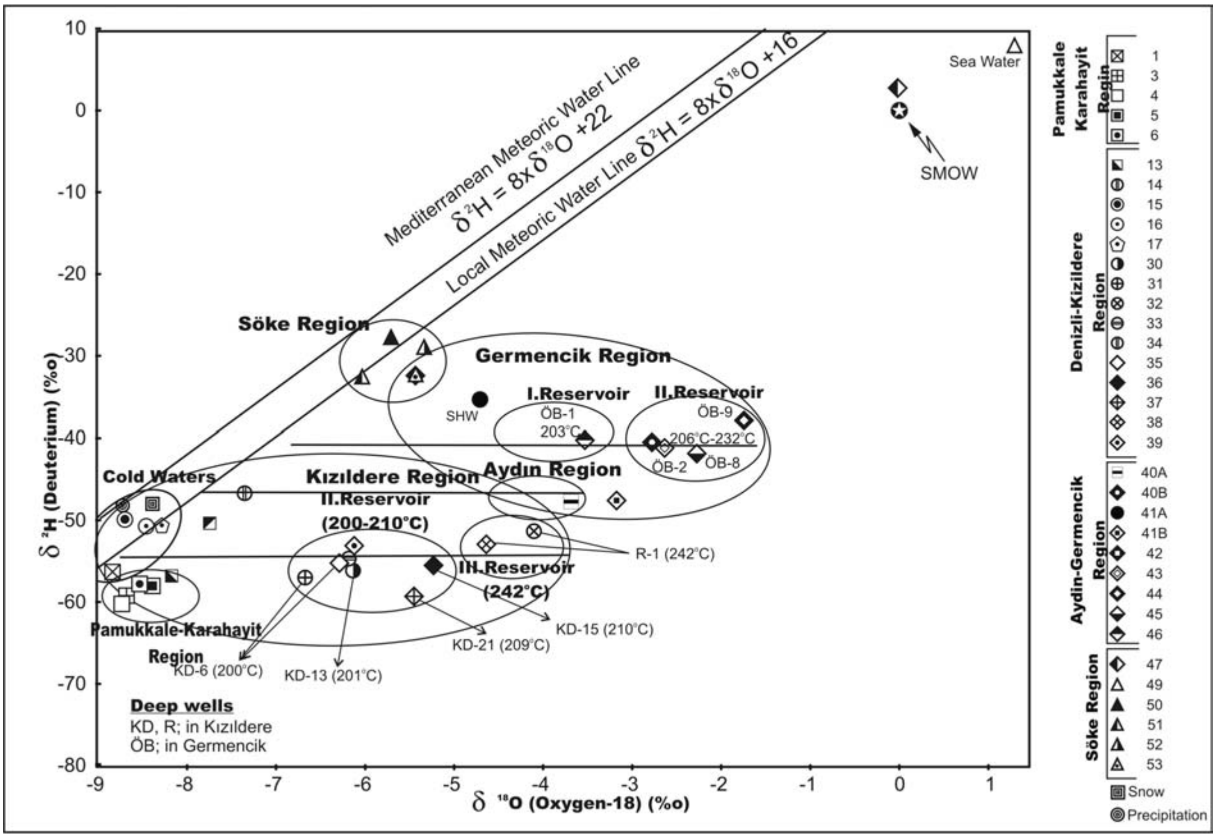

Figure 2. Stable isotope compositions of the geothermal reservoir fluids in the study areas.

The chemical and isotopic compositions of some 12 water samples which were taken from R-1 and other wells (KD-6, KD-13, KD-15, KD-21) from the second reservoir and different temperatures in the field (200-210 ^oC) have been analyzed. These chemical analyses show the water type is $NaHCO_3$ for well R-1, the same as other wells in the field (Table 1). The geothermal water samples have the chemical composition of Na+K>Ca>Mg and HCO_3+ CO_3>SO_4>Cl and on a Na-K-Mg diagram are partially equilibrated fluids [16]. The main geochemical difference between second and third reservoir fluids is HCO_3 and CO_2 contents. The noncondensible gas content of the R-1 (third reservoir) is about %3 by weight while in other wells approximately are %1-1.8. As a result of ^{13}C analyses, the origin CO_2 gas is derived mainly from decomposition of carbonate rocks [9]. Also, a contribution of magmatic CO_2 is important. It is calculated that geothermal fluid in deep reservoirs has low acidic character (pH: 5.5-5.9). A close relation between the data from geothermal wells (maximum 242^o C) and the cation geothermometers (240-260^o C) have been observed.

As a result of the water samples in the Kizildere field, the geothermal waters originated from meteoric origin (Table 2). Hot spring waters and deep geothermal well contain waters almost no tritium so the age of the thermal fluids in the field are older than 50 years.

There is a clear $\delta^{18}O$ shift from the MMWL and cold water values (Figure 2). This suggests that, water-rock interaction is an important process for geothermal fluids according to deep circulation and high temperature effect.

Aydın -Ilıcabaşı and Yılmazkoy-Imamkoy Geothermal Fields

It is expected that the integrated utilization (district heating, greenhouse heating, tourism, balneology etc.) and electricity production from **Imamkoy-Yılmazkoy (Aydin) geothermal field**. This field is located 5 km. east of city center of Aydin [17].The hot spring temperature is 38.5 ºC. The exploration well with a depth of 1500 m. was drilled in 1999. The reservoir consists of Paleozoic marble-schist with a temperature of 142 ºC. The well capacity is 20 l/s. The cap rock consists of Pliocene and Miocene sediments. **Ilicabasi field** is located in the city center of Aydin. It is expected that district heating in the city center of Aydin, greenhouse heating and balneological utilizations from Ilicabasi (Aydin) geothermal field. The exploration wells (DSI-1, DSI-2, AY-1, and AY-2) with the depth of 200 - 471 m. were drilled in 1989 [2]. The reservoir consists of Miocene conglomerate with a temperature is 84-101 ºC. Each of the well capacity ranges between 2.0-4.6 l/s. According to hydrogeology and geothermometer applications it is expected that the second reservoir (marble-schist) at the economic depth with a temperature over than 100 ºC.

Germencik Geothermal Field

This area is located on 100 km west of Kizildere in Western Anatolia. The geological, geophysical and geochemical studies have been performed in Germencik Omerbeyli field [18]. After these studies a total of 9 exploration wells with a depth of 285-2398 m have been drilled between 1982-1987.The temperatures of the first and second reservoirs are found to be 203-217 °C and 216-232 °C. The average flow rate is 300 ton/hour and steam ratio changes from 13% to 20%.

The chemical and isotopic compositions of water samples which were taken from Germencik and Bozkoy hot springs and deep wells (OB-1, OB-2, OB-8, OB-9) have been analyzed (Table 1 and 2). This chemical analysis result shows the water type is NaCl for deep wells, shallow wells and hot springs in the field. The geothermal water samples have the chemical composition of Na+K>Ca>Mg and $Cl>HCO_3+CO_3>SO_4$ or $HCO_3+CO_3>Cl>SO_4$ for shallow well and hot spring waters. The Na-K-Mg diagram most of the well discharge waters are partially equilibrated fluids (Figure 3). It is calculated that geothermal fluids in deep reservoirs have low acidic character (pH: 4.9-5.5). A close relation was obtained between the measured temperatures from geothermal wells and the chemical geothermometers as 230-260^{o}C.

The results of stable isotope results are given in Table 2. The geothermal waters originated from meteoric waters. There is a clear $\delta^{18}O$ shift from the MMWL and cold-low temperature Soke region waters. This suggests that water-rock interaction is an important process for most of chloride hot spring and deep geothermal well waters at Germencik reservoirs.

Table 2. Environmental isotope (^{18}O, ^{2}H and ^{3}H). Data of the cold-hot waters of Pamukkale Karahayit, Denizli-Kizildere, Aydin-Germencik and Soke regions.

Region	Sample No	Sampling date 1998 Sampling Location*	$\delta^{18}O$(%)	$\delta^{2}H$(%)	^{3}H(TU)	(TU) Error ±
PAMUKKALE-KARAHAYIT	1	Karasu CS	-8,45	-56,00	17,4	0,60
	2	Pamukkale PM1 HW	-9,34	-58,00	3,90	0,40
	3	Jandarma HS	-8,87	-59,60	4,50	0,40
	4	Beltes HS	-8,87	-59,50	4,30	0,40
	5	Cukurbag HS	-8,52	-58,60	0,30	0,40
	6	Karahayit HS	-8,32	-57,60	0,00	0,30
DENIZLI-KIZILDERE	11	Gölemezli Well	-8,51	-60,20	0,67	0,29
	12	Yenice CS	-7,88	-51,80	-0,22	0,28
	13	Kamara Well	-8,36	-58,70	0,17	0,17
	14	Bolmekaya HW	-7,84	-47,40	1,05	0,18
	15	Buldan Cus CW	-8,49	-50,00	5,96	0,45
	16	Buldan CW	-8,44	-50,50	0,46	0,32
	17	Ortakci	-8,37	-51,20	0,46	0,16
	30	KD13 HW	-4,64	-34,10	0,09	0,28
	31	KD6A HW	-6,13	-56,20	0,39	0,34
	32	R1 HW	-6,67	-57,00	0,16	0,33
	33	Tekkehamam HS	-4,10	-51,30	0,09	0,33
	34	Tekkekoy CS	-6,18	-54,70	0,21	0,35
	35	KD6 HW	-7,35	-46,70	1,15	0,35
	36	KD15 HW	-5,23	-55,50	0,10	0,34
	37	KD21 HW	-5,45	-59,30	0,24	0,33
	38	R1 HW	-4,64	-52,20	0,26	0,33
	39	İnalti HS	-6,13	-53,50	0,52	0,33
AYDIN-GERMENCIK	40A	Aydin HW	-3,59	-47,80	0,35	0,16
	40B	Bozkoy HS	-2,78	-40,45	0,89	0,34
	41A	Germencik HW	-4,64	-34,10	0,09	0,28
	41B	Bozkoy Cenfined HS	-3,18	-47,60	0,70	0,34
	42	Gumuskoy HW	-5,43	-32,40	5,44	0,41
	43	ÖB2 HW	-2,64	-41,20	0,23	0,33
	44	ÖB9 HW	-1,74	-37,90	0,64	0,33
	45	ÖB8 HW	-2,27	-41,90	0,50	0,33
	46	ÖB1 HW	-3,53	-40,20	0,69	0,33
SÖKE	47	Tuzburgazi HS	-0,02	2,70	1,02	0,35
	49	Sea Water	1,58	9,50	3,03	0,36
	50	Yuvaci CS	-5,71	-27,90	5,45	0,40
	51	Prien-Pinar Rest CS	-6,02	-32,70	6,50	0,42
	52	Davutlar-Thermal HW	-5,34	-29,10	0,84	0,33
	53	Sazlikoy HS	-5,97	-32,50	3,03	0,36
	54	Snow	-8,77	-49,20	4,59	0,28
	55	Precipitation	-8,11	-49,20	4,05	0,29

* Abbreviations: **HW** (hot water well), **HS** (hot water spring), **CS** (cold water spring)

Soke Geothermal Area

This area is situated between Germencik geothermal area and the Aegean Sea. Hot springs are located on the northern flank of the main faults of the Buyuk Menderes Graben and north side of the Gumusdag horst. The temperature range is 20.6-27.5 ^{o}C for springs and 41.7 ^{o}C for well (Davutlar well). The chemical and isotopic compositions of water samples have been collected and analyzed from 3 hot water springs, 2 cold water springs, 1 shallow well and 1 sea water.

Main lithologic formations are karstic marble and schists of Paleozoic age. According to hydrogeological studies water samples collected from karstic springs are Ca>Mg>Na+K and HCO_3+CO_3>Cl>SO_4 (Sazlikoy and Priene springs). There is mixing with karstic water and seawater from inland to Aegean Sea and the water composition changes to Na+K>Mg>Ca and Cl>SO_4>HCO_3+CO_3 character.Evaluation of Na-K-Mg diagram is shown in Figure 3. The position of all the data points indicates that the thermal systems of the Soke region are immature waters.
The stable isotope results are given in Table 2. Isotopic values of cold waters are very close to MMWL equation $\delta^2H=8x\delta^{18}O+22$. Slight deviations from the line show that there is an effect of evaporation on cold waters and they originate from shallow circulation and low temperature system (Figure 2). The isotopic composition of the thermal waters in the Soke areas shows that they are of meteoric origin. Seawater mixing with this water occurs in the west part of Soke, particularly near coast. Seawater flow into the West Soke area is along the main E-W graben fault lines.

5. Conclusions

The hard and brittle lithologies have gained secondary permeability due to active graben tectonism in the region. The first geothermal reservoir in Denizli is limestone (Pliocene) and conglomerates (Miocene) in Aydin. On the other hand, the second reservoir, composed of marble-quartzite unit of the basement, can be used economically. The geothermal fluids rising along the main faults of the grabens in the fields are collected in the permeable zones and migrate to the middle parts of the grabens.

The geothermal waters are mainly of meteoric origin There are three type water type due to chemical composition: a- Na-HCO_3 Kizildere, Germencik, Aydın, b-Ca-HCO_3 Pamukkale-Karahayıt c- Na-Cl mixing with seawater (west Soke region). Evaluation of Na-K-Mg diagram indicates that the geothermal systems of the Kizildere and Germencik fields are partially equilibrated fluids. Geothermometer applications have been encouraged for deep reservoir exploration in Kizildere and Germencik geothermal fields. The results of new exploratory wells show that the geothermometer estimates are reliable for Kizildere (242^o C) and Germencik (232^o C) fields. Geothermal fluids from deep reservoirs in Kizildere and Germencik fields are slightly acidic character as pH: 5.5-5.9 and pH: 4.9 -5.5, respectively.

The absence of tritium in Kizildere and Germencik geothermal waters indicates that residence time of recharging water in the geothermal system is more than 50 years while at the Soke region thermal waters appear to be young in age. There is a clear $\delta^{18}O$ shift from MMWL in Kizildere and Germencik high temperature fields. Also good relation with high temperature and $\delta^{18}O$ shift are determined (Figure 2). It shows deep circulation and water-rock interactions. But, in Soke region low temperature, low shift, shallow circulation and mixing with shallow cold water and seawater are observed.

Acknowledgements
This paper has been carried out within the framework of the IAEA Coordinated Research Program "The Use of Isotope Techniques in Problems Related to Geothermal Exploitation" (HU. UKAM-IAEA Research Contract No 9829/RO-R1) between 1997-1999. Sincere thanks to Ms. J. Gerardo, Z. Pang and staff members of Isotope Hydrology Section of IAEA. The authors deeply thank Prof. Dr. G. Gunay (Director of UKAM) for his support and General Directorate of MTA. The author expresses their appreciation to N. Turkmen from EUAS (Turkish Electricity Authority), Manager of Kizildere Geothermal Power Plant). I also thank

Z. N. Simsek, N. Yıldırım, M.S. Dogdu; B: Akan for field work, E. Oncel and F. Muslu for chemical analyses and H. Karakus and B. Topuz for office work.

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