Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

GEOCHEMISTRY OF THE GERMENCIK GEOTHERMAL FIELDS, TURKEY

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Key Words: Germencik geothermal fields, hydrology, geochemistry, geothermometer, activity diagram

ABSTRACT

The Germencik geothermal fields that are among the most important fields of Turkey. The fields contain two geothermal reservoirs. The first reservoir consists of fractured gneiss and quartz schists, and karstic marbles of the Menderes Massif rocks. Overlying Neogene conglomerates comprise the second geothermal reservoir. Neogene aged clastic sediments, especially clayey levels form the cap rock of the system. The heat source may be near surface magma intruded along the active graben fault zones developed by an extensional tectonic regime. The geothermal waters are high enthalpy, meteoric origin and old. Meteoric waters recharge the reservoir rock, are heated at depth, and move up to the surface by convection.

Five hot water and seven cold water locations were sampled each month for one year to evaluate the hydrogeochemical evolution of geothermal waters and the hydrodynamics of groundwater systems. All thermal waters in the area are of the sodium-bicarbonate-chloride type and the chemistry does not vary temporarily. The measured temperatures of the thermal springs vary from 50°C to 70°C. Estimated reservoir temperatures using various chemical geothermometers and mixing models vary between 150°C and 250°C, which correspond with a high enthalpy system. The estimated reservoir temperatures obtained by Na/K and Na-K-Ca geothermometers coincide with the downhole temperatures (200°C - 232°C) measured directly in nine deep wells. Alteration minerals, which may be formed by the reactions between host rock and thermal fluid, include Ca and Na montmorillonite, Na and K feldspars, zoisite and albite.

1. INTRODUCTION

The geothermal fields in Germencik are divided into two main areas known as the Bozkoy-Camur Geothermal Field and Omerbeyli Geothermal Field. The Germencik geothermal fields are located in the W-E trending Buyuk Menderes graben (Fig. 1). Because of the high geothermal energy potential of the area geological, geochemical, geophysical and isotopic features have been studied by several authors (Simsek et al., 1980; Simsek, 1981; Simsek, 1984; Filiz, 1982; Khayat, 1988; Correia et al., 1990). The first geothermal research was done in 1967 by MTA (General Directory of Mineral Research and Exploration) who continued with deep well drilling in 1982-1986. Drilling studies showed that area has a high geothermal potential with measured deep fluid temperatures of 200°C - 232°C. Isotopic studies also supported these results. The Germencik geothermal fields are considered to have the highest potential in Turkey, approximately 100 Mw(e). Thermal waters, especially from deep wells in the Germencik Geothermal Fields, have high boron contents resulting in a contamination in the field for agricultural purposes. Studies were done here to evaluate geological, hydrological, geochemical properties, fluid chemistry and applicability of chemical geothermometers of the Germencik geothermal fields by synthesising the previous and new data obtained from wells and springs.

Sampling locations for Germencik thermal waters are shown in Figure 1 and their chemical properties are presented in Table 1. Some thermal and cold springs were sampled by Khayat (1989), periodically from October 1986 to October 1987 to evaluate their temporal behaviour. Hot water samples were analysed in DEU Geological Engineering, geochemistry laboratory by the standards of APHA-AWWA-WPCF (1980). Additionally, chemical analyses of waters from deep wells were used from previous studies. Water temperature, electrical conductivity and pH were measured for each sample in the field. Isotopic analyses from UNION (1983), Correia (1990) and Filiz (1982) were used in this study (Table 2).

2.GEOLOGICAL AND HYDROLOGICAL SETTINGS

The basement rocks of the study area are Paleozoic aged Menderes Massif rocks. These rocks include gneiss, schists, metaquartzite and marbles, which occur conformably as lenses in schists. The gneisses have been thrust over the schists. Menderes Massif rocks are unconformably overlain by Neogene (Early Pliocene-Uppermost Pliocene) terrestrial sediments (Simsek, 1984). Quaternary alluvium is the youngest unit of the study area (Fig. 1). The Germencik geothermal fields are controlled by E-W trending faults, which are also form the Buyuk Menderes Graben. Most hot springs are located in the north side of the graben, which is tectonically active. According to the isotopic data, geothermal fluids are of meteoric origin and have high enthalpy (Table 2 and Fig. 2). Since the thermal fluids have hardly any tritium, their minimum ages are assumed at least fifty years. Enrichment of $\delta\ ^{18}O$ values of deep well water and hot springs reflects the high enthalpy fluids in reservoirs of the area.

Meteoric waters which recharge the reservoir rock along faults and fracture zones, heated at depth and move up to the surface through the tectonic lines by convection. The Germencik geothermal systems have two reservoirs. Paleozoic aged fractured rocks including as quartz schist, gneiss and karstic marbles of Menderes Massif are the first reservoir, Neogene aged sandstones, and conglomerates are the secondary reservoir. Neogene aged impermeable claystone and mudstone are the cap rocks (Fig. 1). Heat source is a magmatic intrusion intruded along the young faults by graben tectonism.

3. GEOCHEMISTRY

Analyses of waters sampled by Khayat (1988) and the data from deep wells drilled by MTA in both Germencik geothermal fields were used for this study to evaluate the physical and chemical properties of the geothermal fluids (Table 1). In addition, MTA (1996), Union Oil (1983) and Correia (1990) analyses were also used in to evaluate and interpretate them. In the Germencik Geothermal Field 9 deep wells were drilled by MTA. As a result of the drilling studies, thermal fluids with 203°C – 232°C temperatures and 10% - 12% steam were obtained (Table 3). The water temperatures of hot springs vary between 50^{o}C and 70^{o}C. Electrical conductivity values for thermal springs were about 5500 µS/cm and about 7000 µS/cm for deep well hot water. Electrical conductivity values for cold groundwaters were about 1000 µS/cm (Table 1).

The chemistry of cold groundwaters around Germencik geothermal fields is variable. Thermal waters from springs are dominated by Na^+, HCO_3^-, and Cl^-. However, hot waters from deep wells are characterised by Na^+, Cl^- and HCO_3^-. Na^+ and Cl^- are the main ions in deep well waters (>50 % meq/l). The chemistry of these thermal waters is probably dominated by a combination of mixing with cold waters, mineral dissolution - saturation reactions and ion exchange reactions. Ion concentrations of hot waters from deep wells are higher than those of hot springs. However, their minor constituents are variable. Boron concentrations of thermal waters of the Germencik geothermal fields are high. Boron concentrations of hot springs vary between 40-45 mg/l. However thermal waters from deep wells have higher boron concentrations reaching 63 mg/l (Table 1). Elevated boron is one of the major important hydrogeological problems for cold groundwater aquifers in the area. High boron concentrations of thermal waters result in contamination of cold groundwater aquifers and soils. Boron in thermal waters is considered to originate from the mantle or during metamorphism from marine sediments. Illites and tourmalines in host rocks could be the boron supplier for waters in the study area. To prevent the contamination problem of the cold waters used for irrigational purposes in the study area, re-injection processes of thermomineral waters to the reservoir is necessary.

Temporal sampling suggested that there is no change in pH, electrical conductivity and major ion concentration except for bicarbonate ions in hot springs. Bicarbonate ions in hot springs have shown a remarkable increase in the winter season. Since the bicarbonate ions are the dominant ions in hot springs the increase in bicarbonate ions at the end of the winter season could be related to the changes of the cold groundwater level and mixing of different proportions in cold groundwaters with hot waters. The Piper triangular diagram (Fig. 3) shows that all the thermal waters in the study area are sodium chloride bicarbonate water types. The variations in groundwater geochemistry for the study area along the anticipated flow direction can easily be observed in this Piper diagram.

The saturation indices of hot and cold waters for minerals were calculated by using the Solmineq-88 computer program (Kharaka et al., 1988) using measured temperatures and 1 atm. pressure conditions. Thermal waters of Germencik geothermal fields are oversaturated with respect to calcite, dolomite, and aragonite and undersaturated for gypsum and anhydrite (Table 4). Quartz and chalcedony are also oversaturated with respect to thermal springs but mostly undersaturated for deep well waters. Scaling of calcite and other carbonate minerals are expected for all the thermal waters.

Activity (stability) diagrams in hydrology are based on the estimation of the alteration minerals, which form water and rock interaction. Water-rock interactions of the thermal waters producing kaolinite, muscovite, and albite and anorthite the were investigated using activity diagrams (Fig. 4). Equations used in construction of these diagrams were taken from Kramer (1968) and Tardy (1971). Based on these diagrams, cold groundwaters in the study area are likely to precipitate kaolinite but thermal waters tend to precipitate both kaolinite and montmorillonite minerals (Fig. 4). The difference in kaolinite and montmorillonite stability for hot spring waters and cold waters could be caused by the amount of dissolved silica content. Formation of the montmorillonite needs more silica than that of kaolinite. Because the hot spring waters have higher silica concentrations (reaching 194 mg/l) than those of cold waters with 50-60 mg/l silica, montmorillonite tends to be more stable in hot waters. Figure 5 shows that the thermal waters at 250^{o}C are equilibrated with albite and zoisite.

4. GEOTHERMOMETER APPLICATIONS

In order to estimate the reservoir temperature and geothermal potential of Germencik fields a number of chemical geothermometers and mixing models were applied. Downhole temperatures in the Germencik geothermal fields were measured directly at 200^{o}C-232^{o}C from deep wells by MTA (Table 3). Correlations of the measured reservoir temperatures the results of chemical geothermometers show that Na/K and Na-K-Ca geothermometers are the appropriate geothermometers for Germencik thermal fluids (Table 5). Due to the mixing of thermal waters with waters, thermal spring waters are not fully chemically equilibrated. Therefore, some chemical geothermometers give lower reservoir temperatures than the measured ones.

Chemical geothermometers give reliable results when the water-rock equilibrium is attained. Mixing of thermal waters with cold waters during rise to the surface will not lead to equilibration and the results will be doubtful. Some authors have developed graphical methods based on chemical equilibrium of major ions to determine the applicability of chemical geothermometers. In Figure 6, Giggenbach (1988) divided thermal fluids into three main groups depending on the equilibrium of Na, K and Mg ions as i) fully equilibrated waters ii) partially equilibrated waters and iii) immature waters. Thermal spring waters in the study area are plotted on Figure 6 as immature water. Because of the high proportion of cold groundwater, water-rock interaction of the thermal springs have not equilibrated. Chemical geothermometer results obtained for these waters are considered doubtful, thus calculating the reservoir temperature by the thermal springs mixing models are recommended. Nevertheless, samples obtained from deep wells are plotted as partially equilibrated. Therefore, chemical geothermometers were applied successfully to estimate reservoir temperatures for the waters from deep wells. The measured temperature of OB_2 deep well is 231^{o}C and this value is estimated as the reservoir temperature and correlates with the calculated reservoir temperatures by several geothermometers. Therefore, the applicability of these geothermometers was confirmed. Hot fluids from deep wells OB_1, OB_2, and OB_6 are located in Figure 6 as partially equilibrated and some plot very close to the full equilibrium line. The Na-K-Ca, Na/K and some silica geothermometers give reliable results.

Mixing models (Fournier, 1977b) of the enthalpy-silica diagram (Fig. 7) were used to evaluate the reservoir temperature and mixing ratios of thermal waters with cold groundwaters. The Enthalpy-Silica mixing model is based on heat and silica balance and is useful to evaluate the mixing ratio of cold and hot water components of mixed waters and the reservoir temperatures. The reservoir temperatures were found to be between 170^{o}C – 275^{o}C. The hot water components of thermal waters in the Germencik geothermal fields are 42 % in Camur, 53 % in Alangullu and Balli, 55 % in Ali, 66 % in Ilica, and 83% in OB$_2$ thermal waters.

5. SUMMARY AND CONCLUSIONS

Paleozoic aged fractured rocks including quartz schist, gneiss and karstic marbles of Menderes Massif, which are the basement rocks of the study area, are the deepest reservoirs of lower case Germencik geothermal fields. Neogene aged terrestrial sediments including as sandstones, and conglomerates are the secondary reservoirs and lie on disconformably the Menderes Massif rocks. Neogene aged impermeable claystone and mudstone are the cap rocks (Fig. 1). Geothermal fluids in the Germencik Geothermal Field have a meteoric origin and the tritium content indicates a minimum ages of fifty years. All the thermal waters in the study area are sodium, bicarbonate and chloride water types but hot waters from deep wells are of the sodium, chloride and bicarbonate water type. The chemistry of these thermal waters is probably dominated by a combination of mixing with cold waters, mineral dissolution - saturation reactions and ion exchange reactions.

Electrical conductivity and pH values and major ion concentrations of thermal waters do not change temporarily during a year. However, bicarbonate concentrations increase during the spring and summer seasons reflecting less mixing of thermal waters with cold groundwaters. Depending on the mineral saturation indices, carbonate and silica minerals in thermal springs and carbonate waters in deep wells are expected to cause scaling in wells. Activity diagrams show that thermal waters produce montmorillonite as alteration minerals. The high boron concentrations of thermal waters of the Germencik geothermal fields cause boron contamination of the cold groundwaters and surface waters used in irrigational purposes in the area. This boron contamination in ground and surface waters causes the soil to be contaminated with boron. To prevent boron contamination in cold groundwater aquifers, thermal waters should be reinjected to their own reservoir.

The measured reservoir temperatures from deep wells of Germencik geothermal fields are 200^{o}C-232^{o}C. According to the results of chemical geothermometers, the reservoir temperatures are 150^{o}C-230^{o}C. When correlated with the measured reservoir temperatures, Na/K and Na-K-Ca geothermometers are appropriate for estimating reservoir temperatures for the Germencik geothermal fields. The enthalpy-silica mixing model indicates that hot water components of thermal spring waters are between 42 % and 83 %. Therefore thermal spring waters are not fully equilibrated.

ACKNOWLEDGEMENTS

The authors thank Alan L. Mayo and Halim Mutlu for their useful suggestions and reviews for the some parts of the original manuscript.

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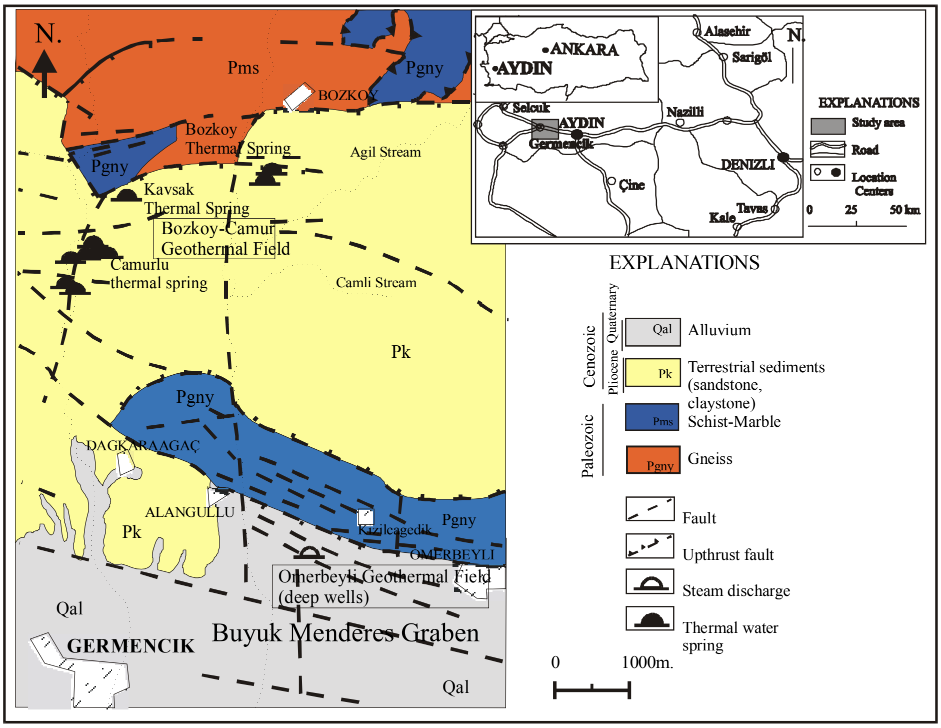

Figure 1. Location map, geological map and sections and the locations of geothermal fields of the study area (geological map was modified from Simsek, 1984).

Table 1. Chemical composition of waters from Germencik Geothermal Field (concentrations are in mg/l).

	Na^+	**K^+**	**Ca^{++}**	**Mg^{++}**	**Cl-**	**HCO_3-**	**CO_3**	**SO_4=**	**B**	**NH_4**	**Li**	**SiO_2**	**T (ºC)**	**pH**	**EC**	**References**
1	1211	116	44	48	1229	2348		60				118	60	7.01	5763	Khayat, 1988
2	1199	125	69	25	1212	2426		66	41			194	60	6.66	5838	Khayat, 1988
3	1101	109	66	58	1115	2355		144	45			131	50	6.9	5383	Khayat, 1988
4	1117	110	57	54	1161	2368		61				147	70	6.63	5783	Khayat, 1988
5	1078	108	39	34	1186	2066		61				146	60	7.6	5292	Khayat, 1988
6	2050	85	3.2	1	1747	2123	438	66	63		7.2	450	200	8.5	7000	Kasap,
7	1355	45	6.4	1	1586	1324	246	37	45	3.8	8	450	200	8.5		Simsek, 1984
8	2810	191	4.2	2	1948	1531	204	168	63		7.4	450	231		7200	Kasap,
9	1600	145	6	1.2	1790	900	280	24	50	9.3	18	480	231	8.7		Simsek,
10	1850	170	0.5	0.5	1970	1868		27.8	58.8		11.6	360		8.38		Correia vd. 1990
11	1260	132	38.6	0.5	1420	1588		38.3	45.2		8	367	221	6.05		Correia vd. 1990
12	112	28	38	77	75	653		78				50	17	7	1171	Khayat, 1988

1-Balli Hot Spring 2-Alangullu Hot Spring 3-Camur Hot Spring 4-Ilıca Hot Spring 5-Ali Thermal Spring 6-OB_1 Weirbox 7-OB_1 weirbox 8-OB_2 weirbox 9-OB_2 2.reservoir 10-OB_6 weirbox 11-OB_6 reservoir 12-Cold Ground Water

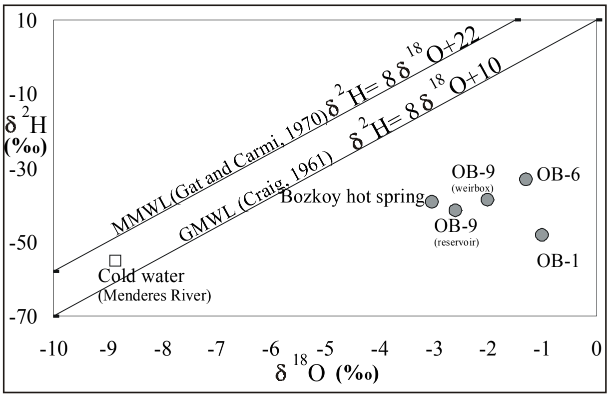

Figure 2. Plot of the δ^2H and δ^{18}O compositions for water samples from Germencik Geothermal Field. GMWL=Global Meteoric Water Line, MMWL= Mediterranean Meteoric Water Line.

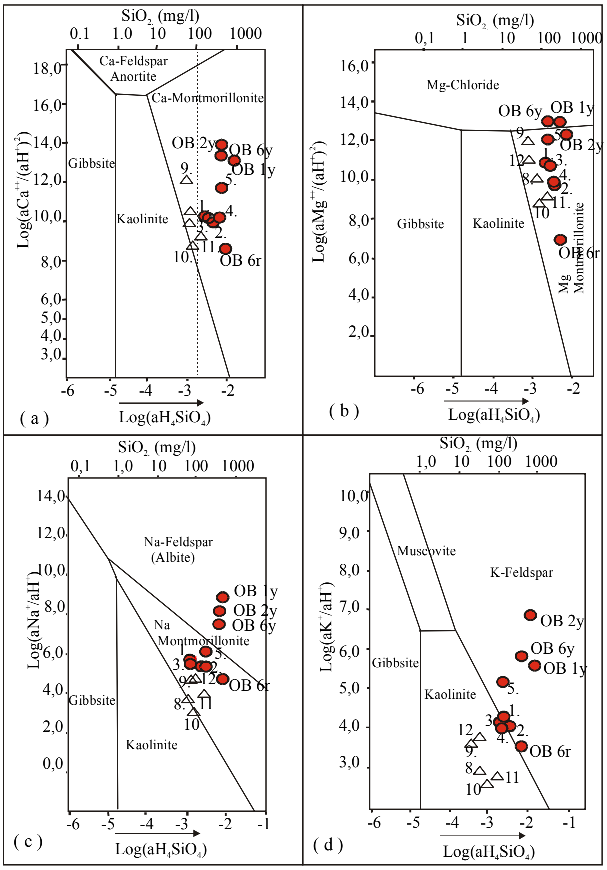

Figure 4. Activity diagrams for hot waters in the study area (25°C, 1 atm.). Activity diagram for a)anortite, Ca-montmorrillonite, kaolinite and gibbsite b)Mg-chlorite, Mg-montmorrillonite, kaolinite and gibbsite c) Na-montmorrillonite, kaolinite and gibbsite d)microcline, muscovite, kaolinite and gibbsite.

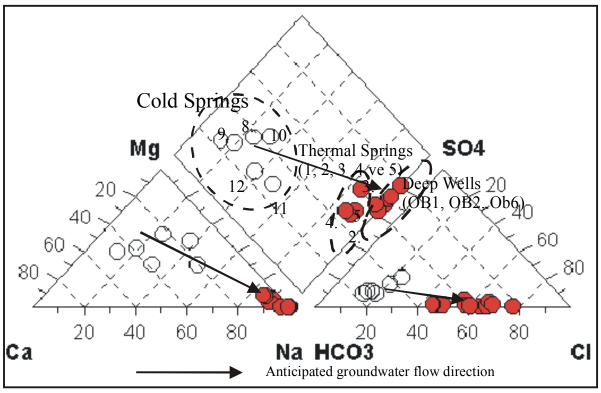

Figure 3. Piper triangular diagram of the waters from the study area (% meq/l)

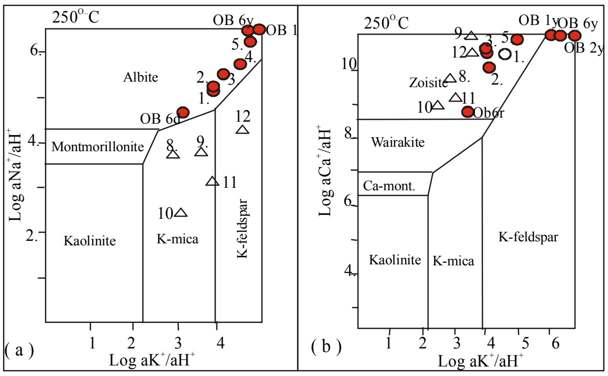

Figure 5. Activity diagrams for hot waters in the study area (250°C) (Henley and Brown, 1985).

Table 2. δ ^{18}O, δ ^{2}H=D and ^{3}H=T (TU) values of some thermal waters in the study area.

Sample Name	Tritium (TU)	δ ^{18}O (‰)	δ ^{2}H=D (‰)	Date	References
Bozkoy Hot Spring	<4	-5.95		1980	Filiz,1982
Cold water (Menderes River)	12-25	-8.85	-54.9	1980	Filiz, 1982
Bozkoy Hot Spring		-3.03	-39	1982	Union Oil,1983
OB-1 well		-1.01	-48	1982	Union Oil,1983
OB-6 well	<1	-1.3	-33		Correia vd,1990
OB-9 weirbox	<1	-2.0	-38.4		Correia vd,1990
OB-9 reservoir	-	-2.6	-41.4		Correia vd,1990

Table 3. Deep wells drilled in Germencik-Omerbeyli Geothermal Fields (MTA,1996) (A:artesien)

Well No	Date	Depth (m)	Temperature (°C)	Discharge (l/s)	Production Type
OB-1	1982	1000	203	Gyser	Geyser
OB-2	1982	975.5	231	25	A(4.5-7 kg/cm^2)
OB-3	1983	1196.7	230	65	A(13-15 kg/cm^2)
OB-4	1984	285	213	180-100	A (15 kg/cm^2)
OB-5	1984	1302	221	65	A (6 bar)
OB-6	1984	1100	221	140	A (15 bar)
OB-7	1985	2398	203	65	A (2.8 kg/cm^2)
OB-8	1986	200	219.87	120	A (5.5 kg/cm^2)
OB-9	1986	1464.7	223.8	145	A (7 kg/cm^2)

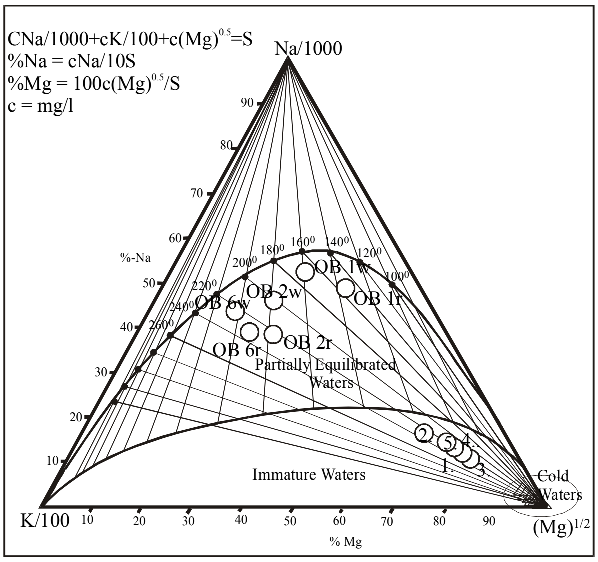

Figure 6. Distribution of the thermal waters in the study area in Na-K-Mg tri-linear diagram (Giggenbach, 1988).

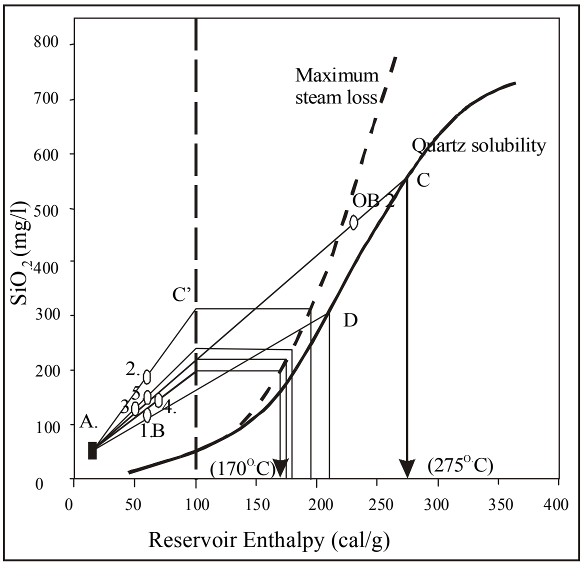

Figure 7. Enthalpy-Silica diagram of waters in the study area (Fournier, 1977b).

Table 4. Mineral saturation indices (SI = Log IAP/Kt) of waters in the study area calculated in respect to the discharge temperature conditions (Negative and positive values indicate the undersaturation and oversaturation, respectively).

	Calcite	Aragonite	Dolomite	Siderite	Magnesite	Quartz	Chalcedony	Gypsum	Anhydrite	Fluorite	Celestite	Barite	Strontionite
1-Ballı Thermal Spring	0.974	0.792	4.691		0.869	0.879	0.951	-3.818	-2.525				
2-Alangullu Thermal Sp.	0.726	0.543	3.462		0.225	1.098	1.285	-3.507	-2.321				
3-Camur Thermal Spring	0.579	0.459	2.734		0.635	1.046	0.796	-2.951	-2.084				
4-Ilıca Thermal Spring	0.449	0.329	2.761		0.672	0.862	0.609	-2.376	-2.324				
5-Ali Thermal Spring	1.080	0.961	3.878		1.228	0.965	0.710	-2.564	-2.585				
6-OB1 (weirbox)	0.879	0.819	3.382	3.145	-0.967	0.055	-0.098	-3.269	-1.856	-2.704			
7-OB1 (reservoir)	1.128	1.068	3.541		-1.058	-0.059	-0.041	-3.044	-1.632				
8-OB2 (weirbox)	0.682	0.629	4.101	3.644	-0.749	0.104	0.032	-3.258	-1.435	-1.414			
9-OB2 (reservoir)	0.761	0.708	2.682		-2.247	-0.162	-0.234	-3.368	-1.547				
10-OB6 (weirbox)	-0.052	-0.107	1.995		-1.873	-0.109	-0.190	-4.366	-2.664		-2.286	-0.125	-0.435
11-OB6 (reservoir)	1.042	0.987	3.437		-1.525	0.076	-0.004	-2.473	-0.768		-3.171	-1.449	-2.123
12-Cold Spring	-1.180	-1.327	0.878		-1.190	1.040	0.878	-2.083	-2.441				

Table 5. Chemical geothermometry results applied on the hot springs in the Germencik Geothermal Field.

		Ballı Thermal	Alangullu (Bozkoy)	Camur	Ilıca	Ali	OB2 Deep
1- SiO_2 (Amophpus silica) (mg/l)	**a**	25	54	31	37	37	124
2- SiO_2 (Alpha christobalite) (mg/l)	**a**	96	128	102	110	109	203
3- SiO_2 (Beta cristobalite) (mg/l)	**a**	47	78	53	60	60	154
4- SiO_2 (Chalcedony) (mg/l)	**a**	121	156	128	136	135	240
5- SiO_2 (Quartz) (mg/l)	**a**	147	178	153	160	159	249
6- SiO_2 (Q-max. Steam loss) (mg/l)	**a**	141	166	146	152	151	223
7- SiO_2 (Chalcedony cond. cooling) (mg/l)	**b**	119	128	125	132	132	226
8- SiO_2 (Q-steam loss) (mg/l)	**b**	117	145	123	129	129	208
9- SiO_2 (Q-steam loss) (mg/l)	**b**	117	152	124	132	131	235
10- SiO_2 (Q-steam loss) (mg/l)	**b**	138	172	145	153	152	251
11- SiO_2 (Q-steam loss) (mg/l)	**b**	140	166	145	151	151	223
12-Na/K (mg/l)	**b**	191	199	194	193	195	159
13- Na/K (mg/l)	**b**	212	219	215	214	216	187
14- Na/K (mg/l)	**c**	179	189	183	182	184	143
15- Na/K (mg/l)	**d**	213	221	216	216	217	186
16- Na/K mol/l	**b**	195	204	198	198	200	162
17-K/Mg (mg/l)	**f**	109	120	104	105	112	180
18-Na/Li (mg/l)	**g**	-	-	-	-	-	432
19- Na-K-Ca mol/l	**c**	208	209	204	206	210	229 (B=1/3)
20-Na-K-Ca meq/l Mg corrected	**h**	45	96	43	43	59	225

(a:Fournier. 1977a; b:Arnorsson et al. 1983; c: Fournier and Truesdell, 1973; d:Fournier, 1979; e: Giggenbach et al. 1983; f: Kharaka and Mariner, 1989; g: Fournier and Potter, 1979)