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GEOLOGY AND GEOCHEMISTRY OF THE SALIHLI GEOTHERMAL FIELDS, TURKEY

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ABSTRACT

The Salihli geothermal fields are located in the southern part of the Gediz Graben, which is one of the Western Turkey grabens. Salihli geothermal systems have been physically divided into four main groups; the Sazdere, Kursunlu, Caferbeyli and Sart-Camur geothermal fields. The reservoir rocks of the geothermal systems are karstic marbles and fractured metamorphic rocks belonging to the Mesozoic Menderes Massif, which is basement in the study area. Since the clayey levels of the overlying Neogene Gobekli and Acidere units have very low permeabilities, they are the cap rock of the systems. Heat sources may be magmatic intrusions closed to surface, rising along the young faults caused by graben tectonism. As with many other geothermal systems in Western Turkey, all the thermomineral waters in the study area are of meteoric origin and circulation in these systems is closely related to tectonic activity.

Most of the thermomineral waters in the study area are of the sodium bicarbonate type. Cold waters in the area are mainly dominated by Ca^{2+}, Mg^{2+}, and HCO_3^- ions, and often have no dominant cation or anion. The major hydrogeochemical processes for thermomineral waters in the geothermal fields are ion exchange between Na^+ and Ca^{2+} and/or Mg^{2+} cations, which are also called natural water softening reactions. The thermomineral waters of the study area fall mostly into the Ca^{2+} and Mg^{2+} montmorillonite fields and partially the kaolinite and K-feldspar fields on the activity diagrams. The waters are mainly undersaturated with respect to carbonate and sulfate minerals. One important environmental problem in the study area is boron contamination in aquifers and soils. The presence of boron is attributed to the geothermal systems of the study area. To prevent boron contamination of cold waters used for irrigation in the study area, re-injection of produced thermomineral waters into the geothermal reservoir is necessary. Assessments of empirical chemical geothermometers and mixing models applied to the thermomineral waters, which have measured discharge temperatures ranging from 37°C to 155°C, suggest that reservoir temperatures vary between 150°C and 230°C. Due to the fact that these waters are not in equilibrium with reservoir rocks, and are probably dominated by a combination of mixing phenomena, rock dissolution and ion exchange reactions, the geothermometer results should be considered tentative.

1. INTRODUCTION

The Salihli geothermal fields are located in the southern parts of the Gediz graben, which is one of the Western Turkey grabens (Fig. 1). The semi-arid climate of the area is characterised by hot dry summers and warm wet winters. The mean annual temperature and the total annual rainfall at Salihli are about 16.5°C and 492 mm, respectively. The region is still active, as the occurrences of earthquakes and the presence of geothermal activities along the graben indicate. Owing to the intense tectonic activity of the study area, many thermal waters, cold springs and running waters were sampled and chemically analysed monthly during the period from 1991 December to 1992 July to define the chemical characteristics of the waters. For samples collected, temperature, pH, and electrical conductivity were measured in the field. The remaining chemical constituents of the waters were analysed later in the laboratory with techniques described in APHA-AWWA-WPCF (1980). This paper discusses the thermomineral waters located in the geothermal fields of Salihli on the basis of hydrological and geochemical assessments.

2. GEOLOGICAL AND HYDROLOGICAL SETTING

Geologic maps and models produced by Emre (1996) were used to explain the relations between geothermal systems and geologic structure. Also were used the same stratigraphic rock units described in Emre (1996). The basement of the study area consists of Menderes Massif rocks, and is made up of high to low grade metamorphics (gneiss, mica schists, phyllites, quartz schists, marbles) and granodiorite. The proposed age of the Menderes Massif rocks ranges from Early Triassic to Uppermost Cretaceous (Erdogan and Gungor, 1992). Neogene sedimentary rocks and Holocene Kula volcanics, which are mainly made up of basaltic lava, unconformably cover the basement rocks (Fig. 1). Neogene-Quaternary sedimentary units occur in different facies in the northern and southern parts of the Gediz Graben, which extends in WNW-ESE direction. The Acidere formation is mainly made up of pebbles, pebbly sandstones, and claystone-mudstones. The Gobekli formation consists mainly of intercalated conglomerate, pebbly sandstone, and sandstone. The Asartepe formation consists of conglomerates comprising sandstone intercalations. The Filiztepe formation, which is exposed in the northern part of graben, consists mainly of limestones. The Mevlutlu formation consists of alternating conglomerate, pebbly sandstone, sandstone and mudstone.

Permeability within the Menderes Massif rocks is highly variable and is related to rock and fracture types. Mesozoic carbonates (marbles and dolomitic marbles) of the Menderes Massif are highly fractured and karstified, and act as a karstic aquifer for both cold and thermomineral waters depending upon location. Granodiorite, gneiss and quartz-schist units of the Menderes Massif rocks form fractured rock aquifers. Where the massif rocks are intersected in topographic lows, numerous cold springs supply soft and very low salinity waters, particularly in the southwestern part of the study area. Where poorly permeable and impermeable rocks such as schist and phyllite units underlie the karstic and fractured aquifers at depth, natural springs are confined to fault and fracture zones and discharge thermomineral waters. Neogene Gobekli and Acidere units, which are made up of granular alluvial fan deposits including poorly cemented clayey levels, have very low permeabilities and form the cap rocks of the geothermal systems. The shallow regional aquifer consist of Holocene alluvial deposits in the middle of the study area, and of Pleistocene Mevlutlu formations composed of alluvial deposits in the north.

The Salihli geothermal fields are divided into four main groups from west to east in the active southern rims of the Gediz Graben as the Horzum-Sazdere thermal springs, the Kursunlu thermal springs, the Sart-Camur thermal springs, and the Caferbeyli Geothermal Field (Fig. 1). The Horzum-Sazdere thermal springs (two springs) are located along the easternmost part of the east-west directional tectonic line in the southern rims of the graben. These thermomineral springs discharge waters at 3 l/s and at a temperature of 35°C. They are not used. Kursunlu geothermal field has a shallow reservoir about 200 meters deep and contains hot springs and wells (Fig. 2). The depth from surface of the reservoir in this geothermal field varies between 10 – 200 meters (Yilmazer and Karamanderesi, 1994). The total discharge rate for the MTA_1, MTA_2 and MTA_3 wells is 145 l/s and average production temperatures are 90°C. Sart-Camur thermal springs are situated along the westernmost part of the southern rim of the Gediz Graben. Thermomineral waters in Kursunlu and Sart-Camur geothermal fields are now used for bathing and medicinal purposes. Caferbeyli Geothermal Field is situated between Sart-Camur and Kursunlu fields. When well drilling, was done here in 1990, the downhole temperature was found to be 155°C at 1189 meters (Karamanderesi, 1997). Owing to the low system permeability and resulting low discharge rate (about 2 l/s) economic fluid production was not possible from this well.

As with many other geothermal systems in Western Turkey, the circulation of the thermomineral waters in Salihli geothermal fields is closely related to major fault and fracture zones. Fractured rocks of the Menderes Massif, such as quartz schists, gneiss and granodiorite and karstic marbles, are the reservoir rocks in the Salihli geothermal fields. The discharge rates are high where the reservoir is predominantly formed by marbles. Since the clayey levels of the Neogene Gobekli and Acidere units are relatively impermeable, they act as the system cap rock. Heat sources may be magmatic intrusions closed to surface intruded via young faults. Meteoric waters circulate in the Salihli geothermal systems. The meteoric waters penetrate through the faults and fractures, are heated in reservoir rocks, and move up to the surface along the faults. Isotopic data (^{18}O and ^{2}H) suggests that thermal waters in Salihli geothermal fields are of meteoric origin although $\delta\ ^{18}O$ rich (Filiz et al., 1992).

3. GEOCHEMISTRY

The results of the chemical analyses of the waters sampled from the study area are listed in Table 1. Major constituents, EC, pH, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^-, SO_4^{2-} and SiO_2 and some secondary constituents, K^+ and B^{3+} values were obtained by calculating mean annual values during the period from 1991 December to 1992 July. The remaining constituents are values from 1992 July. The locations of the water samples are shown in Fig. 1 and Fig. 2. Monthly periodic analytical results show no significant changes in temperatures and chemical constituent concentrations with time for thermomineral waters in the Salihli geothermal fields. However cold waters, particularly stream waters, showed significant variation in ion concentrations. Na^+, HCO_3^- and B^{3+} concentrations for the Kursunlu Stream increase in summer months due to reduced flow and a corresponding increase in the contribution of thermomineral waters to the stream. Thermomineral waters from Salihli geothermal fields exhibit similar chemical characteristics, having $Na^+ > (Ca^{2+}+Mg^{2+}+K^+)$ and $HCO_3^- > (Cl^- + SO_4^{2-})$. The Sazdere thermomineral spring is enriched in Mg^{2+}. The Sart-Camur spring and MTA_2 well are also enriched in Ca^{2+} as well as Mg^{2+}. The variations in groundwater geochemistry for waters in the study area along the anticipated flow direction can also be observed in a Piper diagram (Fig. 3). The chemistry of all the thermomineral waters of the study area is mainly dominated by Na and HCO_3^- ions (>50 %). Sart-Camur thermal spring and MTA_2 thermal well waters are a Na^+-Ca^{2+}-HCO_3^- (Ca^{2+}>20 %) water type, and Sazdere thermal spring water is a Na^+-Mg^{2+}-HCO_3^- (Mg^{2+} >20 %) water type. The other thermomineral waters are Na-HCO_3^- rich (all unmentioned ions are < 20 %). Cold waters in the study area are different. Dominant ion species are generally Ca^{2+} and/or Mg^{2+}. Some waters have no dominant cation species; HCO_3^- and/or SO_4^{2-} are generally the dominant anions. The differences reflect different lithologic and mineralogic controls on water chemistry due to differing flow patterns, and recharge sources. Qualitatively, the Ca^{2+}-Mg^{2+}-HCO_3^- water probably reflects the dissolution of calcite and dolomite in the aquifer matrix. The chemical reactions involved in the dissolution of the carbonate minerals are a combination of hydrolysis and dissociation. Other sources of Ca^{2+}-Mg^{2+}-HCO_3^- and Na^+ ions in cold waters are silicate weathering and alteration reactions.

However, the high concentrations of Na^+ and HCO_3 ions in the thermomineral waters of Salihli geothermal fields cannot be explained by only dissolution of carbonate and silicate minerals. These thermomineral waters are probably dominated by a combination of mixing phenomena, rock dissolution and ion exchange reactions. The chemical composition of the thermomineral waters clearly differs from that of the cold waters. Compared to the local cold groundwaters and stream waters, all the thermal waters are enriched in Na^+ and HCO_3^-. This high concentration of Na^+ in thermal waters of Salihli and the crystalline basement host rock suggests silicate weathering and alteration. However, if silicate weathering was the dominant reaction in the geothermal reservoirs, there should be indications of the presence of SiO_2 in the geothermal fields. However, there is no SiO_2 cementation near the thermal springs. If dissolved Ca^{2+}, Mg^{2+} and HCO_3^- in both cold and thermal water results mainly from the dissolution of carbonate minerals, then the proportions of Ca^{2+} and/or Mg^{2+} versus HCO_3^- should be linear. The correlation coefficients (r) of these ions mentioned above in the waters of the study area vary from 0.08 to 0.10, which indicate a very poor fit (Table 2). On the contrary, the correlation coefficient between Na^+ and HCO_3^- ions is 0.86. This is a good fit. This shows a positive linear relationship between Na^+ and HCO_3^- ions. In addition, there are negative correlations and a very poor fit between Na and Ca^{2+} cations. In accordance with the above, the increase in sodium and the decrease in calcium and magnesium in the thermomineral waters can be explained by ion exchange. It would follow the generalised reaction,

$M^{2+} + Na_2\text{–}Clay = 2Na^+ + M\text{–}Clay$ (1) Where, M^{2+} is Ca^{2+} or Mg^{2+} or other alkaline earth metals. Generally, the chemical reactions involved in the dissolution of carbonate minerals (for calcite) can be summarised as;

$CaCO_3 + CO_2 + H_2O = Ca^{2+} + 2HCO_3^-$ (2)

In the above reaction, it is considered that roughly, half of the dissolved HCO_3^- comes from carbonates, and the rest is from the reaction of removing Ca^{2+} (and/or Mg^{2+}) from the water. For Ca^{2+} the most likely possibility appears to be the natural softening reaction of cation exchange for Na^+ on clay levels of schists or Neogene sediments as discussed below;

$Ca^{2+}+2Na_{ex}=Ca_{ex}+2Na^+$ (3)

If this equation (3) is combined with the former reaction (eqn. 2), We obtain

$CaCO_3+H_2CO_3+2Na_{ex}=Ca_{ex}+2Na^++2HCO_3$ (4) or

$Ca^{2+}+2(HCO_3^-)+solid\text{-}2Na^+=2Na^++2(HCO_3^-)+solid\text{-}Ca^{2+}$ (5)

Dissolution of host rocks as a function of fluid temperatures occurs at all sites. The hot waters are mixed with different proportions of cold groundwater and the ion exchange occurs through the circulation path of the thermomineral waters.

Major hydrogeochemical processes for cold waters in the study area seem to be carbonate solution and silicate weathering reactions. The major hydrogeochemical processes in the geothermal fields is ion exchange, which is also referred to as natural water softening and occurs between Na^+ and Ca^{2+} and/or Mg^{2+} cations. Solution of calcareous materials in geothermal systems leads to an increase in Ca^{2+} which is then exchanged for Na^+ from clay minerals (a number of clayey levels are associated with the cap rocks of the Salihli geothermal systems). Such a process yields a $NaHCO_3$ type groundwater, which also has a thermal and mineral water character (Tarcan and Filiz, 1997).

One of the major environmental problems for cold waters in the study area is boron contamination of aquifers and soils. Boron contents of the thermomineral waters are quite high (Table 1). Boron is well correlated with chloride, sodium, bicarbonate and silica in the all waters of the study area (Table 2). This suggests that the cause of the high boron contents in cold groundwaters and surface waters is thermomineral fluids issuing from the Salihli geothermal fields. All the thermomineral waters are mainly HCO_3^- dominated and B^{3+} and HCO_3^- are well correlated with each other. Therefore, HCO_3^- is probably the main anion responsible for the high boron content in the thermomineral waters. To prevent boron contamination of cold waters used for irrigational purposes, re-injection of produced thermomineral waters to the geothermal reservoir may be necessary.

It is important to know saturation indices for minerals to predict which ones may precipitate during the extraction and use of the waters. A saturation index of zero indicates that thermodynamic equilibrium exists with the solid phase. A negative or positive index indicates undersaturation and oversaturation, respectively. Mineral saturation indices for 13 mean annual water analyses were calculated on the basis of measured surface temperatures using the Solmineq.88 (Kharaka et al., 1988) computer program (Table 3). All of the waters are undersaturated with respect to gypsum and anhydrite, and oversaturated with respect to quartz and chalcedony, except for Kursunlu Ufuruk cold spring. All saturation indices for calcite, aragonite, dolomite, siderite and magnesite reflect undersaturation except for the Caferbeyli deep well and the Sazdere thermomineral spring waters. These results coincide with the field observations. Gypsum and anhydrite minerals have not been observed in the aquifer systems and there is a paucity of travertine near the springs.

4. GEOTHERMOMETER APPLICATIONS

A number of solute geothermometers were used to estimate the reservoir temperature of some of the thermomineral waters in Salihli geothermal fields (Table 4). Some results of the geothermometers seen in Table 4 are impossible since they are lower than the measured surface temperatures. Discarding these data, the rest of the data can be used to estimate the reservoir temperature. The geothermometry results suggest the reservoir temperatures of Salihli geothermal fields are between 150°C - 230°C. Solute geothermometers give reliable results when the water-rock interactions reach equilibrium. Mixing of thermal waters with cold waters while moving up to the surface will not lead to equilibration and thus the results are doubtful. A ternary plot of $Na/1000\text{-}K/100\text{-}Mg^{0.5}$ was proposed by Giggenbach (1988) as a method to determine reservoir temperature and to recognize waters, which have attained equilibrium with the host lithology (Fig. 4). The graphical representation of the combined geothermometer for this study is illustrated in Fig. 4. All the thermomineral waters in the Salihli geothermal fields fall into the immature fields indicating none of these waters have attained equilibrium with their associated host rocks. Because these waters are not in equilibrium with reservoir rocks, and are probably dominated by rock dissolution, mixing with cold groundwater, and ion exchange, geothermometer results can only be considered tentative. Hence, the applications of cation geothermometers must be considered in doubt and correlated with the results obtained by mixing models to predict the reservoir temperature. The thermal waters in the study area have a fast hydrological circulation and/or mix with the cold groundwaters along the flow path to the surface. Geothermometry techniques appear to be unreliable for these waters because none of the fluids are at equilibrium with reservoir rocks.

Enthalpy-Chloride and Enthalpy-Silica mixing models were proposed by Fournier (1977b) to estimate reservoir temperatures and the mixing rates of the cold and hot water components of mixing waters (Fig. 5 and Fig. 6). The estimated reservoir temperatures obtained by the enthalpy chloride mixing model for the thermomineral waters in Salihli geothermal fields are from 194°C to 288°C (Fig. 5). The hot water components of the thermomineral waters obtained by the enthalpy chloride mixing model are 33% in Sart Camur, 55% in Celikli, 56% in Kursunlu, 62% in MTA_2, and 73% in MTA_3. The reservoir temperatures obtained by the enthalpy silica mixing models were found to be between 187°C and 227°C (Fig. 6). The hot water components of the thermomineral waters (mixing ratios) in the study area obtained by the enthalpy silica mixing model vary from 27 % to 90 % (Sazdere=27%, Celikli=34%, Sart Camur=36%, MTA_3=45%, Caferbeyli=75%, MTA_2=81%, Kursunlu=90%).

5. SUMMARY AND CONCLUSIONS

Fractured rocks such as gneiss, quartz schist and granodiorite, and karstic rocks such as marbles of the Menderes Massif form the basement reservoir rocks of Salihli geothermal fields. Neogene aged Acidere and Gobekli units, including clayey levels, are the cap rocks of the Salihli geothermal systems. Heat sources may be magmatic intrusions closed to the surface via the young faults. All the thermomineral waters are of meteoric origin. Meteoric waters which percolate through the faults, cracks, fissures, and karstic voids are heated at depth and then are convected to the surface. As with many other geothermal systems in Western Turkey, the circulation of the thermomineral waters in the study area is closely related to tectonic activity. Thermomineral waters of the Salihli geothermal fields exhibit similar chemical characteristics, having $Na^+ > (Ca^{2+}+Mg^{2+}+K^+)$ and $HCO_3^- > (Cl^-+SO_4^{2-})$. Cold waters in the study area reflect different water types. Dominant ion species are generally Ca^{2+} and/or Mg^{2+}. Some waters have no dominant cation; HCO_3^- and/or SO_4^{2-} are generally the dominant anions. Monthly analytical results showed no significant changes in temperatures and major and secondary constituents with time for the thermomineral waters in the Salihli geothermal fields. However, sodium, bicarbonate, and boron concentrations of cold waters increase during the summer season.

Geochemical evolution of thermal waters progresses from alteration reactions of silicates and carbonates to ion exchange reactions. All the thermal waters in the study area ultimately become a sodium bicarbonate water due to ion exchange reactions between Na^+ and Ca^{2+} and/or Mg^{2+} cations. Major hydrogeochemical processes in the study area are a combination of mixing phenomena, rock dissolution, and ion exchange reactions. The waters are mainly undersaturated with respect to gypsum and anhydrite and oversaturated with respect to the quartz and chalcedony. All the saturation indices for calcite, aragonite, dolomite, and magnesite minerals reflect undersaturation except for the Caferbeyli deep well and Sazdere thermomineral spring waters. One of the most important environmental problems is boron contamination of cold groundwaters and surface waters used for irrigational purposes by mixing with rising thermal waters. Thermomineral waters should be reinjected to their own reservoir to prevent boron contamination of soil and water. This process would also recharge the geothermal systems. The reservoir temperatures calculated from the cation geothermometers, except for the Mg corrected Na-K-Ca geothermometer, are generally higher than those of silica geothermometers. Chemical geothermometers and mixing models indicated that the reservoir temperatures of Salihli geothermal field vary between 150°C and 230°C. Enthalpy-Chloride and Enthalpy-Silica mixing models indicated that the hot water components of the thermal waters range from 27% to 90%. All the thermomineral waters in Salihli geothermal fields fall into the immature field of these plots indicating none of these waters have attained equilibrium with their associated host rocks. Since thermomineral waters of the fields are not equilibrated in water-rock interactions, chemical geothermometers were not successful in estimating reservoir temperature.

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REFERENCES

APHA-AWWA-WPCF (1980). *Standard Methods for Examination of Water and Waste Water*. Fifteenth Edition, Copyright by Am. Pub. Health As. Washington D.C. 1193 pp.

Arnnorsson, S., Gunnlaugsson, E., and Svavarsson, H. (1983). The chemistry of geothermal waters in Iceland. III. Chemical geothermometry in geothermal investigations. *Geoch. et Cosm. Acta*, vol. 47, pp. 567-577. Pergamon Press. USA.

Emre, T. (1996). Gediz Grabeni'nin jeolojisi ve tektonigi. *Turkish Journal of Earth Sciences.* Tubitak, no. 5, pp.171-185, (in Turkish, special issue).

Erdogan, B., and Gungor, T. (1992). Menderes Masifi'nin kuzey kanadinin stratigrafisi ve tektonik evrimi. *TPJD Bult*. Vol.. 4/1 pp.9-34 (In Turkish).

Filiz, S., Gokgoz, A., and Tarcan, G. (1992). Hydrogeologic comparisons of geothermal fields in the Gediz and Buyuk Menderes Grabens. *XI. Congress of World Hydrothermal Organisation. 13-18/V/1990, Istanbul-Pamukkale-Turkey, Proceedings*, pp.129-153.

Fouillac, C., and Michard, G., 1981, Sodium/Lithium ratio in water applied to the geothermometry of geothermal waters. *Geothermics,* Vol.10, pp.55-70.

Fournier, R.O. (1977a). A Review of chemical and isotopic geothermometers for geothermal systems. In *Proceedings of the Symp. on Geot. En. Cento Sci. Prog*., Ankara, pp.133-143.

Fournier, R.O. (1977b). Chemical geothermometers and mixing models for geothermal systems. In *Proceedings of the Symp. on Geoth. Ene. Cento Sci. Prog*., Ankara, pp.199-210.

Fournier, R.O., and Potter, R.W. (1979). Magnesium Correction to the Na-K-Ca Chemical Geothermometer. *Geochimica et Cosmoschimica Acta*, Vol. 43, pp.1543-1550.

Fournier, R.O., and Truesdell, A. H. (1973). An Empirical Na-K-Ca Geothermometer for Natural Waters. *Geochimica et Cosmochimica Acta*, Vol.37, pp.1255-1275.

Giggenbach, W. F. (1988). Geothermal Solute Equilibria. Derivation of Na-K-Mg-Ca Geoindicators. *Geochimica et Cosmochimica Acta*, Vol.52, pp.2749-2765.

Giggenbach, W. F., Gonfiantini, R., Jangi, B.L., and Truesdell, A.H. (1983). Isotopic and Chemical Composition of Parbati Valley Geothermal Discharges, NW Himalaya, Indiana. *Geothermics*, Vol. 5, pp.51-62.

Karamanderesi, I.H. (1997). Salihli-Caferbeyli (Manisa Ili) jeotermal sahasi potansiyeli ve gelecegi. *DEK TMK, Turk 7. En. Kong. Tekn. Ot. bil. met*., pp.247-261, (In Turkish).

Kharaka, Y.K., Gunter, W. D., Aggarwal, P. K., Perkins, E. H., and De Braal, J. D. (1988). *Solmineq.88: A computer Program Code for Geochemical Modelling of Water-Rock Interactions*. In U.S.Geological Survey Water Investigations Report 88-05,

Tarcan, G., and Filiz, S. (1997). Hydrogeology of the Turgutlu Geothermal Field. *Turkish Journal of Earth Sciences*, vol.6, no.2, pp.43-64.

Yilmazer, S., and Karamanderesi, İ.H., 1994, Kursunlu jeotermal alaninin (Salihli-Manisa) jeolojisi ve jeotermal potansiyeli. *Dun. En. Kon..Turkiye 6. En. Kong., TMK, 17-22 Ekim 1994, Izmir, Tek. Ot. Tebl.* Vol.I, pp.68-181, (In Turkish).

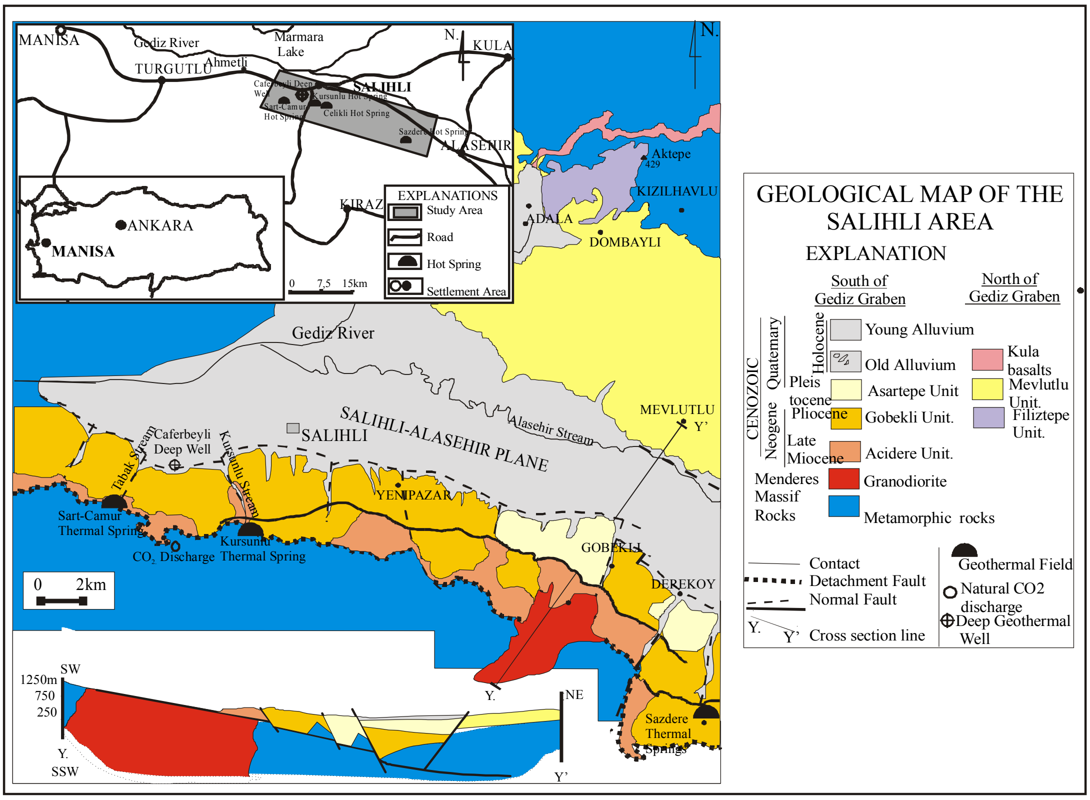

Figure 1. Location, geological map and cross section of the study area and locations of geothermal fields (modified from Emre, 1996)

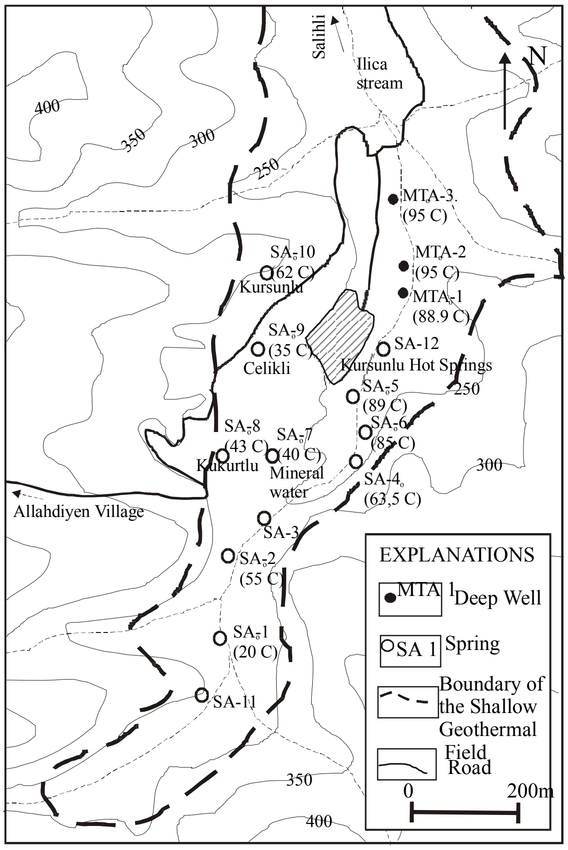

Figure 2. Spring and well locations in the Kursunlu geothermal field (modified from Yilmazer and Karamanderesi, 1994).

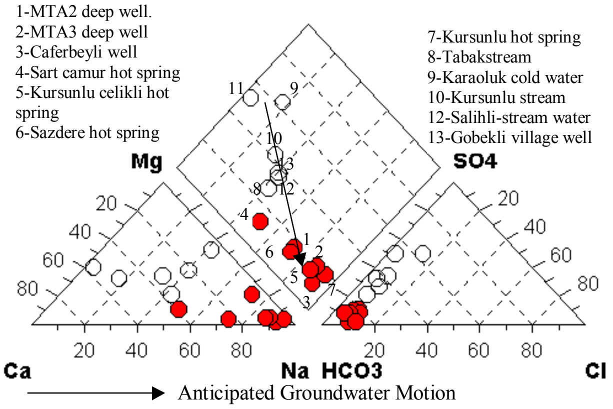

Figure 3. Piper trilineer diagrams of the waters from the study area

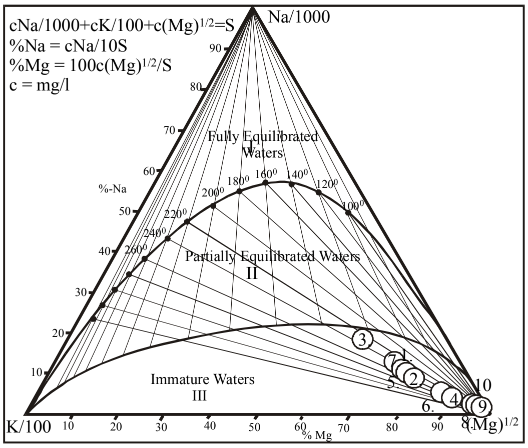

Figure 4. Distribution of the thermal waters from the study area in Na-K-Mg tri-linear diagram(Giggenbach, 1988).

Table 1. Chemical Analyses of Waters from the Salihli Geothermal Fields (Concentrations are in ppm, T (°C)=measured temperature)

Sampling No and Name	Date	T (°C)	EC□S/cm	PH	Na	K	Ca	Mg	Fe	Li	Mn	Ni	Cu	Pb	Cl	HCO3	SO4	SiO2	B
1-MTA2 Tw	25.4.1992	85	3000	6.3	462	55	130	13	0.100	Nd	nd	0.147	0.008	0.076	69	1378	125	267	65
2-MTA3 Tw	24.6.1992	95	2750	6.03	431	50	31	13							90	1220	100	135	31
3-Caferbeyli Tw	20.9.1990	155	2700	7.8	680	70	42	6	0.100	Nd	nd	0.147	0.008	0.076	115	1983	34	214	67
4-Sart-Camur Ts	An. Av.	51	1431	6.03	199	24	134	23	0.133	1.8	0.04	0.082	0.006	0.057	37	1076	81	101	13
5-Celikli Ts	An. Av	42	2310	5.98	500	62	45	15	0.063	1.788	0.005	0.120	0.008	0.087	68	1513	119	182	23
6-Sazdere Ts	21.5.1993	37	3070	7.55	417	50	29	65							200	2477	43	145	
7-Kursunlu Ts	An. Av.	90	1850	4.85	426	51	10	9	0.110	1.842		0.103	0.005	0.072	64	1080	107	186	38
8-Tabak Stream Sw	An. Av.	20	586	7.10	45	6	34	12							16	305	73	29	2.3
9-Karaoluk Cs	An. Av.	14	210	7.25	5	1	13	5	0.054	0.014	nd	0.022	0.005	0.033	14	66	71	11	nd
10-Kursunlu Stream Sw	An. Av.	19	410	6.76	29	4	26	16	0.072	0.082	nd	0.033	0.004	0.038	16	204	92	19	3
11-Kursunlu Ufuruk Cs	31.5.1992	15	1420	5.75	12	7	180	77							21	647	541	2	
12-Salihli Stream Sw	21.5.1993	18	1299	7.19	140	15	17	92							41	535	174	19	
13-Gobekli Village Cw	21.5.1993	18	556	4.9	30	4	14	15							12	293	120	26	

Tw=Thermal well, Ts=Thermal spring, Sw= Stream water, Cs= Cold spring, Cw= Cold well, An. Av. = Annual averages (from 1991 Dec. to 1992 July), Nd not determined.

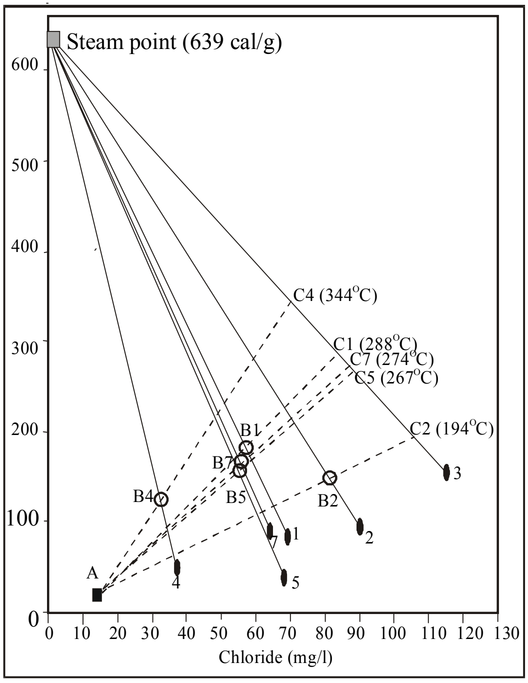

Figure 5. Enthalpy-Chloride diagram of waters in the study area.

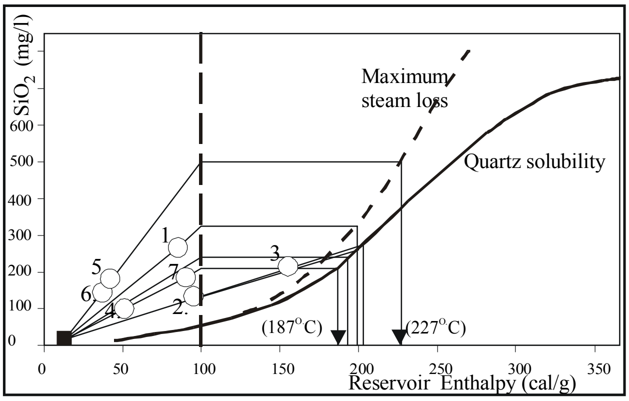

Figure 6. Enthalpy-Silica diagram of waters in the study area

Table 2. Correlations of the chemical parametres of the waters in the study area (Concentrations are in meq/l)

	Na	K	Ca	Mg	Cl	HCO_3	SO_4	SiO_2	pH	B	EC
Na	1,0	0,9	-0,05	-0,24	0,72	0,86	-0,37	0,92	-0,12	0,86	0,89
K		1,0	-0,01	-0,22	0,72	0,87	-0,32	0,92	-0,18	0,83	0,91
Ca			1,0	0,26	-0,12	0,10	0,65	0,08	-0,40	0,22	0,20
Mg				1,0	0,18	0,08	0,57	-0,34	0,44	-0,59	0,07
Cl					1,0	0,93	0,32	0,62	0,18	0,88	0,81
HCO_3						1,0	-0,24	0,76	0,03	0,81	0,92
SO_4							1,0	-0,36	-0,17	-0,06	-0,11
SiO_2								1,0	-0,40	0,96	0,85
PH									1,0	-0,34	-0,18
B										1,0	0,85
EC											1,0

Table 3. Mineral saturation indices of waters calculated in respect to the discharge temperature conditions

	Calcite	Aragonite	Dolomite	Siderite	Magnesite	Quartz	Chalcedony	Gypsum	Anhydrite
MTA 2. Well (85°C)	-0.09	-0.21	1.48	-0.28	-0.19	0.96	0.72	-2.04	-1.84
MTA 3. Well (95°C)	-2.28	-0.38	1.20	-	-0.37	0.56	0.33	-2.08	-1.77
Caferbey well	1.99	1.92	5.83	0.42	1.19	1.20	0.05	-2.39	-1.41
Sart-Camur Ther. Spring (37°C)	-0.12	-0.24	0.62	-1.01	-0.79	0.92	0.67	-1.59	-1.67
Kursunlu Thermal Spring (90°C)	-2.03	-2.13	-2.02	-1.70	-1.80	0.75	0.52	-2.51	-2.25
Celikli Thermal Spring (42°C)	-0.65	-0.77	-0.25	-1.43	-1.11	1.29	1.04	-1.98	-2.13
Sazdere Thermal Spring	0.80	0.67	3.44	-	1.13	1.25	1.01	-2.74	-2.93
Tabak Stream	-0.36	-0.51	-0.75	-	-1.10	0.74	0.30	-1.98	-2.22
Karaoluk spring	-1.35	-1.45	-2.59	-	-2.13	0.40	-0.06	-2.29	-2.54
Kursunlu Stream	-1.03	-1.18	-1.82	-	-1.54	0.58	0.13	-1.98	-2.22
Kurs.Ufuruk Spring	-0.88	-1.03	-1.57	-	-1.57	-0.34	-0.81	-0.77	-1.01
Salihli Stream	1.64	1.50	4.37	-	2.15	0.40	-0.03	-2.12	-2.34
Gobekli Well	-2.91	-3.06	-5.45	-	-3.10	0.61	0.18	-2.15	-2.37

Table 4. Chemical geothermometry results applied on the hot springs in the study area

GEOTHERMOMETERS	K.T.S. (90 °C)*	K.C.T.S (42 °C)*	S. C T.S. (51 °C)*	K MTA 2. Well (85 °C)*	KMTA 3 well (95 °C)*	H.S.T.S. (37 °C)*
a- SiO_2 (mg/l) (Amorphous Silica)	52	50	17	76	33	37
a- SiO_2 (mg/l) (Alpha cristobalite)	125	124	87	152	104	109
a- SiO_2 (mg/l) (Chalcedony)	153	151	111	183	130	135
a- SiO_2 (mg/l) (Quartz)	175	173	137	201	154	159
a- SiO_2 (mg/l) (Quartz max. steam loss)	164	163	133	185	147	151
b- SiO_2 (mg/l) (Chalcedony cond. cooling)	148	146	109	175	127	131
b- SiO_2 (mg/l) (Quartz steam loss)	149	147	107	178	126	131
b- SiO_2 (mg/l) (Quartz steam loss)	164	162	132	185	146	150
b- Na/K (mg/l)	214	218	215	214	211	165
b- Na/K (mg/l)	230	233	231	230	227	192
c- Na/K (mg/l)	206	210	207	205	202	150
d -Li (mol/l)	177	176	176	-	-	-
d -Na/Li (mol/l)	176	160	251	-	-	-
e- K/Mg (mg/l)	109	107	77	106	103	84
c- Na-K-Ca (mol/l)	216 □=1/3	181 □=4/3	94 □=4/3	139 □=4/3	180 □=4/3	182 □=4/3
f- Na-K-Ca – Mg corrected (meq/l)	81	88	not applicable	116	79	7

(KTS=Kursunlu thermal spring, KCTS= Kursunlu-Celikli thermal spring, SCTS= Sart Camur thermal spring, KMTA2=Kursunlu MTA2 well, KMTA3=Kursunlu MTA3 well, HSTS=Horzum Sazdere thermal spring, a= Fournier 1977b; b= Arnorsson et al. 1983, c= Fournier and Truesdell 1973, d= Fouillac and Michard 1981, e= Giggenbach et al. 1983, f= Fournier and Potter 1979)