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Geothermal Fields Along the North Anatolian Fault Zone (NAFZ): Assessment of Geothermal Potential

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ABSTRACT

A total of 7 geothermal fields, covering a west-to-east transect of about 530 km along the North Anatolian Fault Zone (NAFZ), were sampled in 2000 and 2001 in an attempt to assess their geothermal potential. The studied fields are, from west to east, Efteni, Mudurnu, Bolu, Seben, Kurşunlu, Gözlek and Reşadiye. Both production wells and natural springs were utilized during sampling.

The temperature of thermal waters ranges between 38 and 73 ^{o}C, and the pH values between 5.6 and 7.5. TDS content varies, by a factor of about 25, from 433 to 11074 mg/l. Thermal waters are almost all Na-HCO_3 type except those from Bolu and Mudurnu which are Ca-Mg-SO_4 and Ca-HCO_3 type waters, respectively. The waters appear to have acquired their chemical character mainly through the dissolution of their reservoir rocks that are dominantly Mesozoic limestones, and/or through ion-exchange reactions on the way to surface. The chemical composition of waters, when examined together with their discharge temperatures, suggests the occurrence of subsurface mixing and conductive cooling in the geothermal fields of Kurşunlu, Seben and Mudurnu.

Cation geothermometers yielded overestimated, whereas amorphous silica, cristobalite and opal CT geothermometers yielded underestimated temperatures for most of the geothermal fields. Chalcedony temperatures are almost similar to the discharge temperatures. The estimates from quartz geothermometer appeared to be more representative as they are also supported by silica-enthalpy and chloride-enthalpy mixing models applied to Kurşunlu and Seben fields. In this respect, the likely reservoir temperatures are in the range of 88-115 ^{o}C for Kurşunlu, 85-88 ^{o}C for Bolu, 143-150 ^{o}C for Efteni, 77-86 ^{o}C for Mudurnu, 110-149 ^{o}C for Seben, 97-99 ^{o}C for Reşadiye and 67-72 ^{o}C for Gözlek geothermal fields.

From the point of geothermal potential, Efteni and Seben fields appear to be more promising for geothermal energy development. However, precautions should be taken against possible silica and calcite scaling.

1. INTRODUCTION

Owing to its setting within the tectonically active Alpine–Himalayan belt, Turkey has a high potential in terms of geothermal energy sources. The widespread geothermal activity in Turkey manifests itself in the form of numerous hot springs, fumaroles and recent mineralization, the distribution of which roughly parallels the distribution of the fault systems

In this study, we evaluate the geochemical characteristics and the geothermal potential of the fields located along the North Anatolian Fault Zone (NAFZ) which is one of the major neotectonic structures in Turkey (Figure 1). The samples, including both hot and cold waters, were collected from 7 localities (Figure 1, Table 1) in two different periods, June 2000 and April 2001. The sampled localities are Bolu (town-center), Gölyaka-Efteni (Bolu), Mudurnu-Babas (Bolu), Seben-Pavlu (Bolu), Kurşunlu-Çavundur (Çankırı), Gözlek (Amasya), and Reşadiye (Tokat). The samples were analyzed for their major anion-cation and silica contents at the laboratories of the Department of Geological Engineering, Middle East Technical University (Ankara, Turkey). The results of analyses were used i) to determine the hydrogeochemical facies, ii) to evaluate the possible subsurface processes, iii) to estimate the reservoir temperatures and to assess the geothermal potential through the use of various geothermometers, and iv) to infer about possible scaling problems via an examination of the saturation state of hot waters with respect to calcite and silica.

2. TECTONIC AND GEOLOGIC SETTING

The present-day tectonic deformation in Turkey, that has been governed since the Late Miocene by the relative convergence between the Afro-Arabian and the Eurasian plates, is concentrated in four main structures: Bitlis Suture Zone (BSZ), North Anatolian Fault Zone (NAFZ), East Anatolian Fault Zone (EAFZ), and Western Anatolian Graben System (WAGS) (Figure 1). The NAFZ is a right-lateral strike-slip fault, about 1500 km long and a few hundred meters to 40 km wide (Mc Kenzie, 1972; Dewey and Şengör, 1979; Arpat and Şaroğlu, 1975; Barka, 1992). Although its western and eastern limits are not well defined (see Bozkurt, 2001 for a review), the NAFZ extends from Karlıova in the east (where it meets the EAFZ) towards the Gulf of Saros in the west. The fault zone has a mostly single fault trace for about 900 km between Karlıova and Dokurcun. To the west of Dokurcun town (Figure 1), it is split into several branches characterized by dominant normal faulting component along with strike-slip component (Canıtez and Üçer, 1967; Mc Kenzie, 1972; Dewey and Şengör, 1979).

The tectonic activity along the NAFZ is accompanied by a geothermal activity concentrated particularly in the western and central-western segments of the zone. Paleozoic metamorphics, along with Mesozoic limestones and flysch, comprise the basement rocks in the geothermal fields (Erişen et al., 1996). Volcanic activity, extending from Late Cretaceous to Miocene, is represented by basaltic-andesitic lava flows, tuffs and agglomerates Tertiary is composed of terrestrial, especially lacustrine sediments. Quaternary alluvium, and in some fields travertines, form the youngest units.

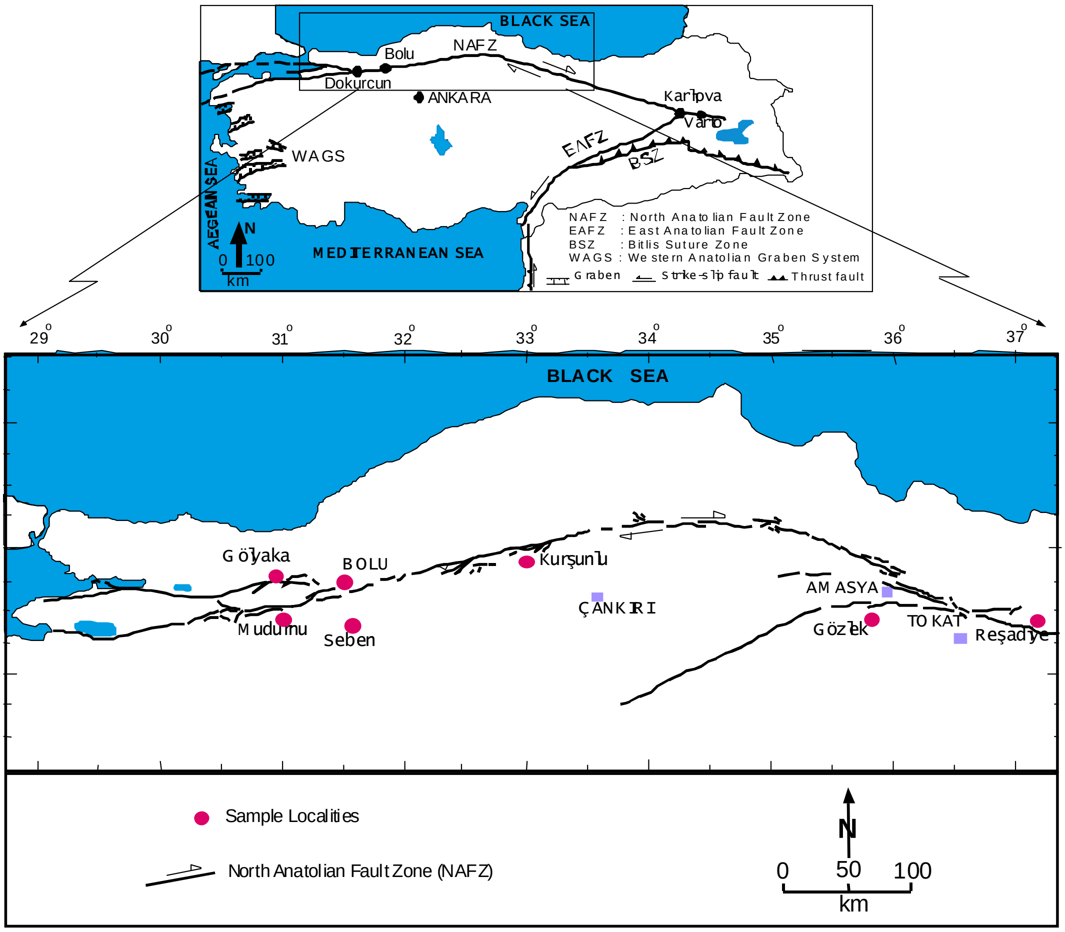

Figure 1: Sample locality map.

Table 1. Information relevant to samples and sampling localities

Locality	*Temperature (ºC)	**Sample Type** (Depth of producing zones for production wells are given in parentheses)
Kursunlu-Çavundur	56	Production Well (165 m)
Kursunlu-Çavundur	16	Spring (mineral water)
Kursunlu-Çavundur	14	Spring
*Bolu Hamamlari	45	Production Well (83 m)
		Production Well (150 m)
Efteni-Gölyaka	44	Spring
Efteni-Gölyaka	19	Spring
Babas-Mudurnu	39	Production Well – 80 m
Babas-Mudurnu	40	Production Well – 125 m
Babas-Mudurnu	25	Spring
Babas-Mudurnu	17	Spring
Seben-Pavlu	73	Spring
Seben-Pavlu	58	Production Well – 4 m
Seben-Pavlu	47	Production Well – 2.5 m
Seben-Pavlu	17	Spring
Resadiye-Tokat	46	Spring
Gözlek-Amasya	41	Production Well – 800 m

*sampling was performed from two different wells in June 2000 and April 2001 periods (the well sampled in 2000 was already out of production at the time of sampling in 2001).

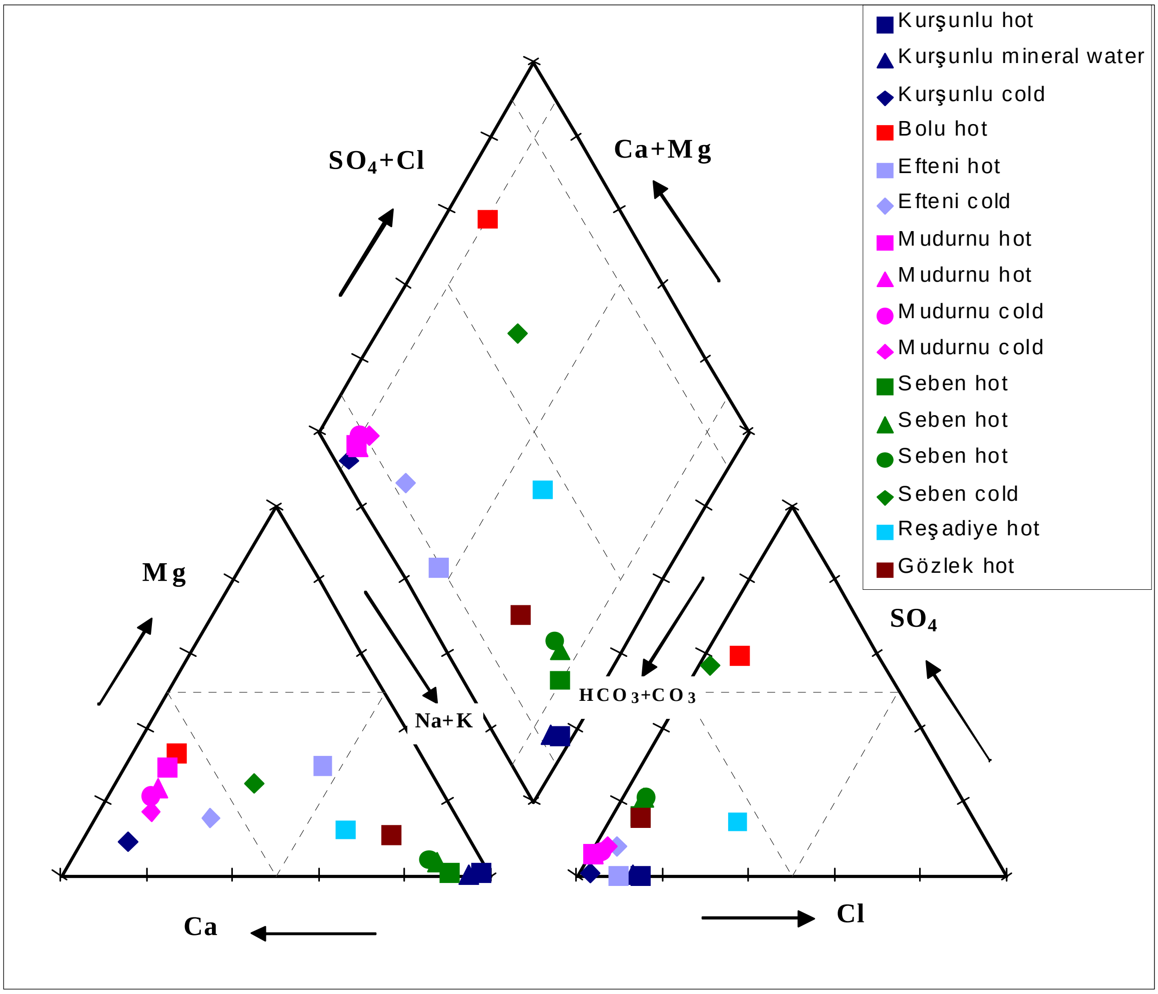

Figure 2. Piper diagram showing the hydrogeochemical facies of the samples.

In the majority of the geothermal fields included in this study, the primary reservoir rocks are comprised of Mesozoic limestones and the cap rocks are the impervious clayey levels of Tertiary sediments (Canik, 1971, 1972; Şahinci, 1971; Şentürk and Ünay, 1976; Özcan and Ünay, 1978; Müftüoğlu and Akıncı, 1989; Eşder et al., 1996). Only in Kurşunlu field, Tertiary volcanics act as the main reservoir rock (Koçak, 1974).

3. HYDROGEOCHEMICAL CHARACTERISTICS

The temperatures of the hot waters range between 38 and 73 °C, whereas those of the cold waters range between 13 and 19 °C (except one sample from Mudurnu which is relatively warmer with a temperature of 25 °C). All the waters are slightly acidic to neutral in character with pH values ranging from 5.6 to 7.5 for the hot, and from 5.7 to 7.8 for the cold waters.

The hot waters are characterized by high TDS contents ranging between 433 and 11074 mg/l, the lowest and the highest values belonging to Gözlek and Kurşunlu samples, respectively. The cold waters have lower TDS contents (362 - 866 mg/l), although one of the cold water samples from Kurşunlu has a considerably high TDS content (approaching that of the hot water sample in the concerned field) and is considered as "mineral water".

The hydrogeochemical facies of samples are determined using Piper diagram (Figure 2). Since the results of chemical analyses of samples collected in June 2000 and April 2001 do not show much variaiton to cause any change in the hydrogeochemical facies, the data used in the diagrams throughout this paper are the mean values of the 2000 and 2001 periods.

As can be seen from Figure 2, the waters are dominantly Na-HCO_3 type except Bolu and Mudurnu samples which have Ca-Mg-SO_4 and Ca-HCO_3 character respectively. While HCO_3 character seems to be compatible with the type of reservoir rocks that are dominated by limestones, the dominancy of Na cation is probably a result of ion exchange processes with the overlying lacustrine sediments.

The hydrogeochemical characteristics of samples are also depicted in terms of Schoeller diagram (Figure 3) where waters of similar nature yield similar ionic profiles.

4. EVALUATION OF SUBSURFACE PROCESSES

Since Cl is usually considered to be one of the most useful tracers owing to its relatively "conservative" nature, Cl vs. discharge temperature plots are used for the evaluation of subsurface physico-chemical processes (Figure 4). Since more than two samples could be collected in only three fields (Kurşunlu, Mudurnu and Seben), the evaluation could be performed here only for the concerned three fields. The cold water and the hot water samples are taken as end members, and the possible effects of mixing, and adiabatic and conductive cooling are indicated in the diagrams.

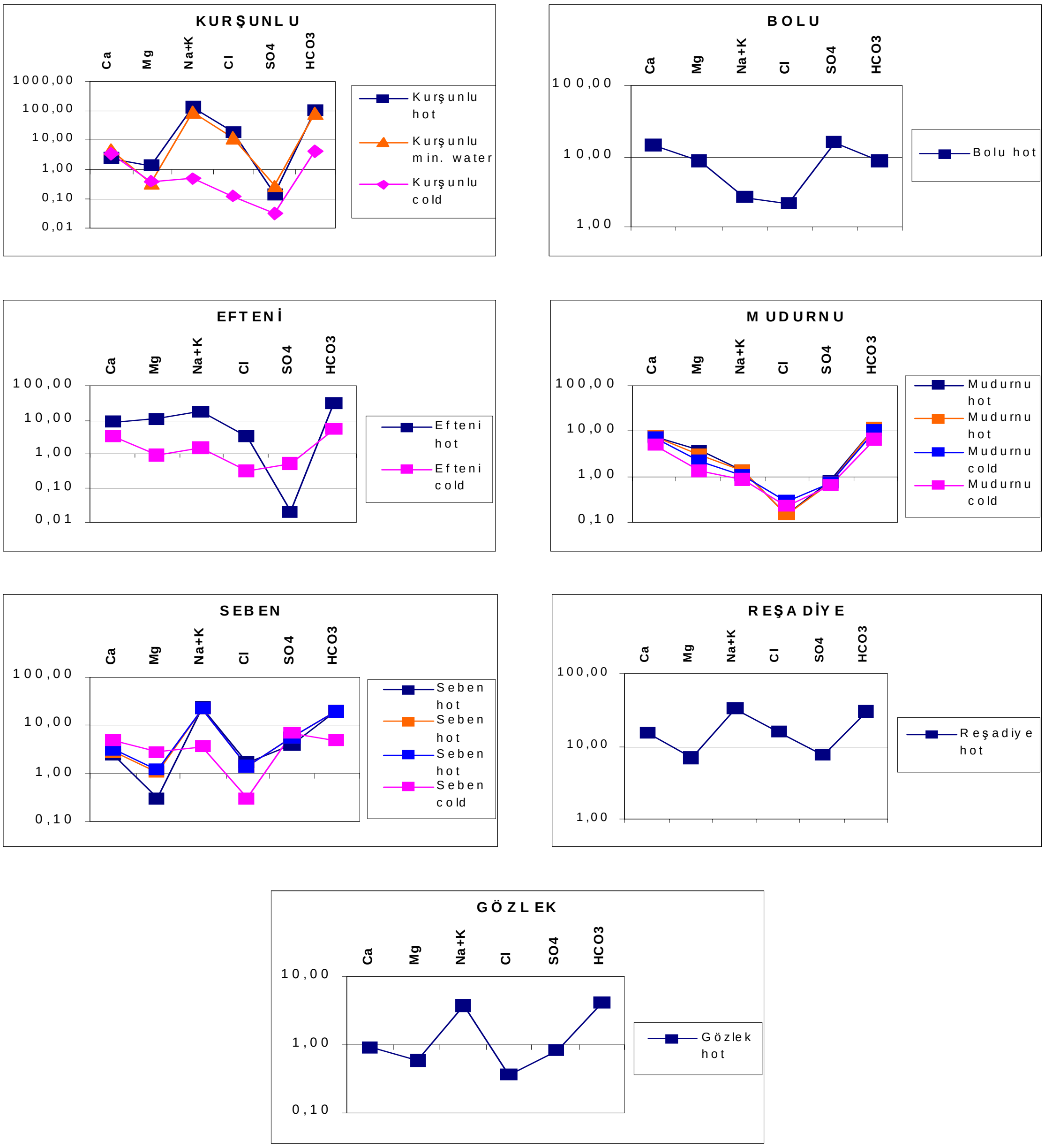

Figure 3. Schoeller diagram for samples.

An examination of Figure 4 implies the prevalence of mixing and further conductive and/or adiabatic cooling in Kurşunlu, Mudurnu and Seben fields. However, given the fact that the temperature of mixed waters are rather low for boiling (lower than the temperature of the hot water components, namely 56 °C for Kurşunlu, 40 °C for Mudurnu and 73 °C for Seben fields), the possibility of adiabatic cooling can easily be eliminated. In this respect, mixing and conductive cooling appear to be the major subsurface processes in the studied geothermal fields.

5. GEOTHERMOMETRY APPLICATIONS

5.1. Silica and Cation Geothermometers

The results of silica and cation geothermometers applied to the studied geothermal fields are represented in Figure 5 and 6, respectively.

Regarding the silica geothermometers, since Opal-CT and amorphous silica temperatures yield anomalously low temperatures (lower than the measured discharge temperatures), the results of cristobalite, chalcedony and quartz geothermometers are given in Figure 5. As can be seen from Figure 5, chalcedony and cristobalite temperatures (Fournier, 1977; Arnorsson et al., 1983) give results similar to, or slightly higher than discharge temperatures. Quartz geothermometers (Fournier, 1977; Fournier and Potter, 1982; Arnorsson, 1985), on the other hand, appear to yield more reasonable estimates from 88 to 91 °C for Kurşunlu, 85 to 88 °C for Bolu, 143 to 150 °C for Efteni, 77 to 86 °C for Mudurnu, 111 to 115 °C for Seben, 97 to 99 °C for Reşadiye and 67 to 72 °C for Gözlek fields.

Na/K geothermometers (Truesdell, 1976; Tonani, 1980; Arnorsson et al., 1983; Fournier, 1979; Nieva and Nieva, 1987; Giggenbach, 1988) yield anomalously high estimates (around 300-400 °C) for Mudurnu and Bolu fields; the results for the other fields are also considerably high ranging from 100 to 200 °C (Figure 6). The anomalous estimates for Bolu and Mudurnu fields probably stand from the Ca-rich character of the waters, as Na/K geothermometer may not work properly for waters having high Ca contents. To eliminate the possible effects of Ca concentrations on Na/K geothermometer, Na-K-Ca geothermometer of Fournier and Truesdell (1973) was used. For Bolu and Mudurnu, it yields lower temperatures than

Na/K geothermometer, around 55 °C and 35 °C, respectively, the latter being an underestimate as it is lower than the measured discharge temperature. For Kurşunlu, Seben and Reşadiye fields, Na-K-Ca estimates are similar to those obtained from Na/K geothermometer. Since calcite scaling is a major problem in Kurşunlu production well, and since travertine deposition currently occurs in Reşadiye, the measured Ca contents of these waters are lower than those supposed to be in reservoir conditions. This implies that the Na-K-Ca temperatures should be overestimates for the concerned fields. It then appears that Na-K-Ca geothermometer and the Na/K geothermometer (giving similar results with Na-K-Ca geothermometer) are not much reliable for the studied fields. Likewise, K-Mg geothermometer (Giggenbach, 1988) does not yield reasonable estimates as they are rather similar to discharge temperatures for most fields. In this respect, quartz geothermometers seem to work best for the studied geothermal fields.

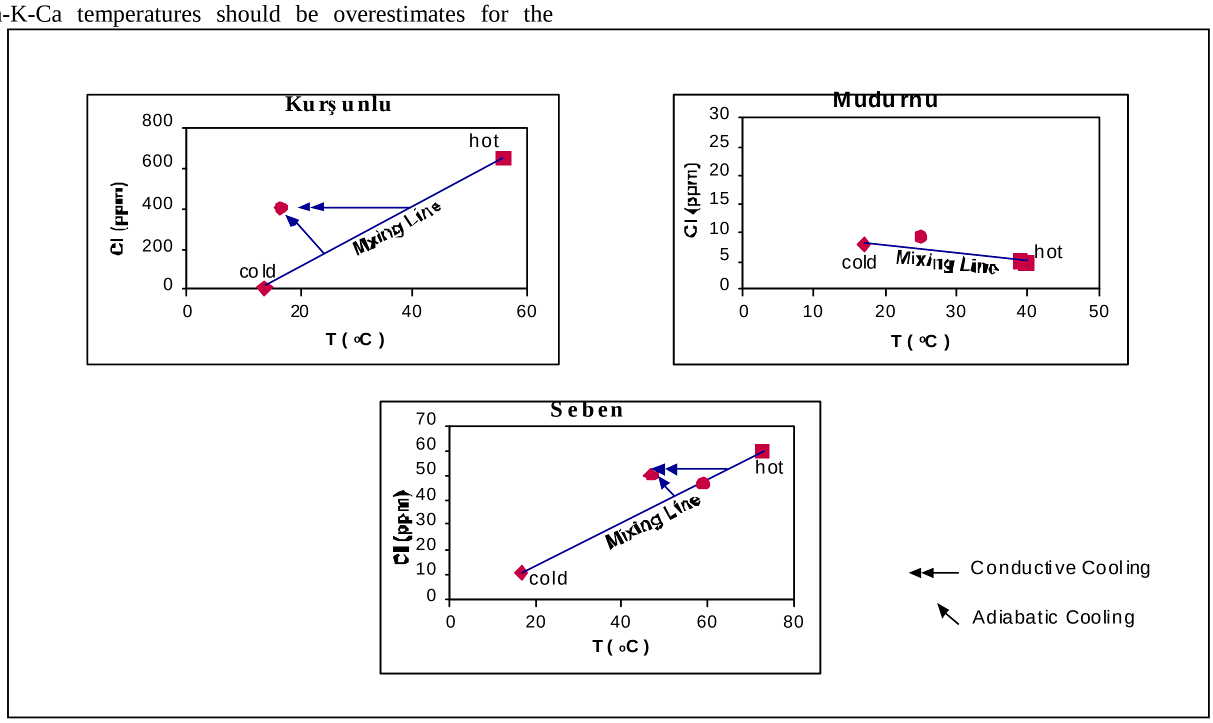

Figure 4. Cl vs. discharge temperature diagrams for Kurşunlu, Mudurnu and Seben samples.

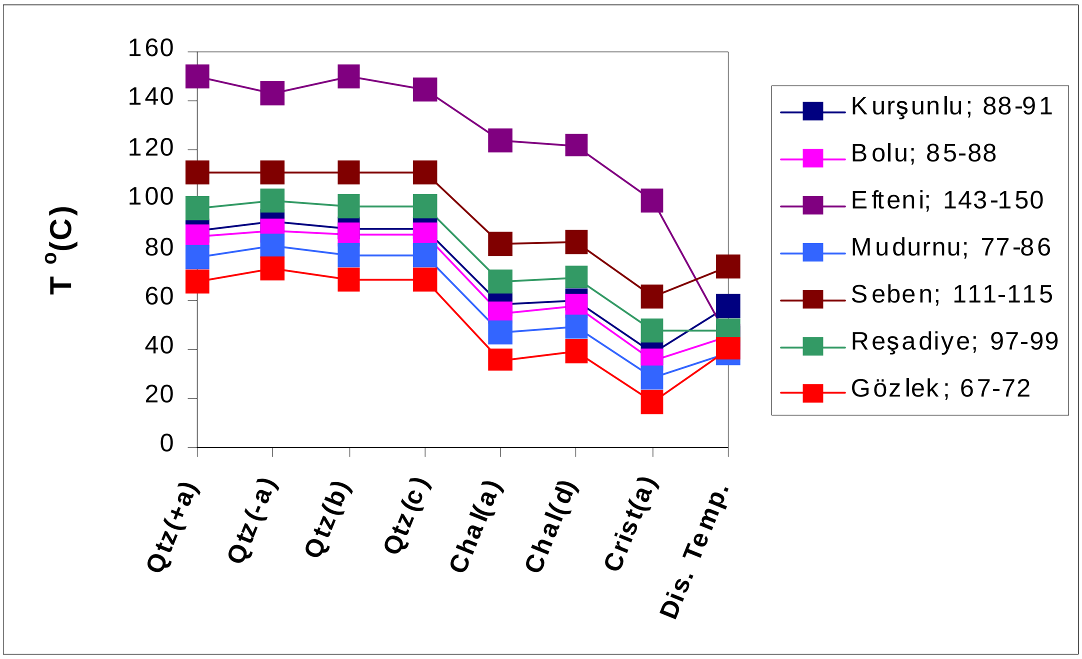

Figure 5. Diagram depicting the results of silica geothermometry applications. The numbers in front of the sample locality names give the range of temperatures (°C) obtained from quartz geothermometers. Qtz: quartz geothermometer, Chal: chalcedony geothermomer, Christ: cristobalite geothermometer, Dis. Temp: discharge temperature, a: Fournier (1977) (a+: qtz.- no steam loss, a-: qtz-max. steam loss); b: Fournier and Potter (1982); c: Arnorsson (1985); d: Arnorsson et. al. (1983).

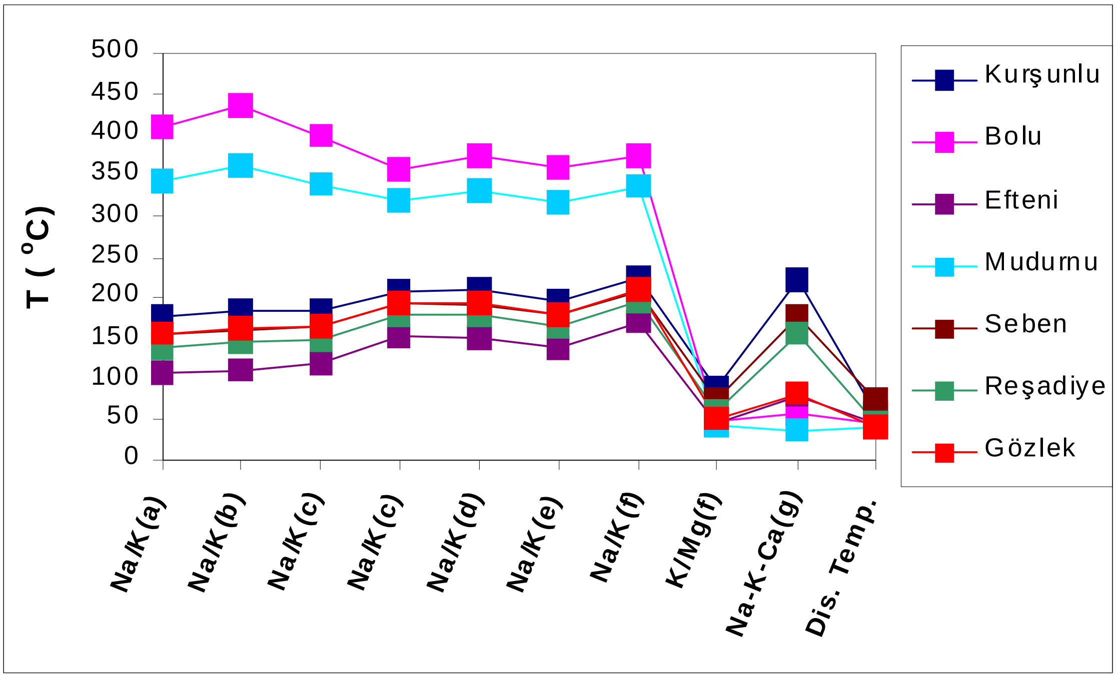

Figure 6. Diagram depicting the results of cation geothermometry applications. a: Truesdell (1976), b: Tonani (1980), c: Arnorsson et al. (1983), d: Fournier (1979), e: Nieva and Nieva (1987), f: Giggenbach (1988), g: Fournier and Trusdell (1973). Dis. Temp: discharge temperature.

5.2. Silica-Enthalpy and Chloride-Enthalpy Mixing Models

A further assessment of the reservoir temperatures is made here via the use of silica-enthalpy (Fournier, 1977) and chloride-enthalpy (Truesdell and Fournier, 1975) mixing models.

The application of silica-enthalpy and chloride-enthalpy mixing models requires the use of adequate number of (hot and cold water) samples for individual fields. In this respect, Seben , Kurşunlu and Mudurnu appear to be the most appropriate fields to be utilized in the models. However, for Mudurnu field, since i) no silica analyses could be performed on cold waters, and ii) the Cl content of cold waters are similar to those of hot waters, only Seben and Kurşunlu fields could be examined in the mixing models.

In silica-enthalpy diagram (Figure 7), the mixing line connecting the hot and the cold water components intersects the quartz solubility curve at an enthalpy value of 625 J/g for Seben field, corresponding to a reservoir temperature of 148-149 °C.

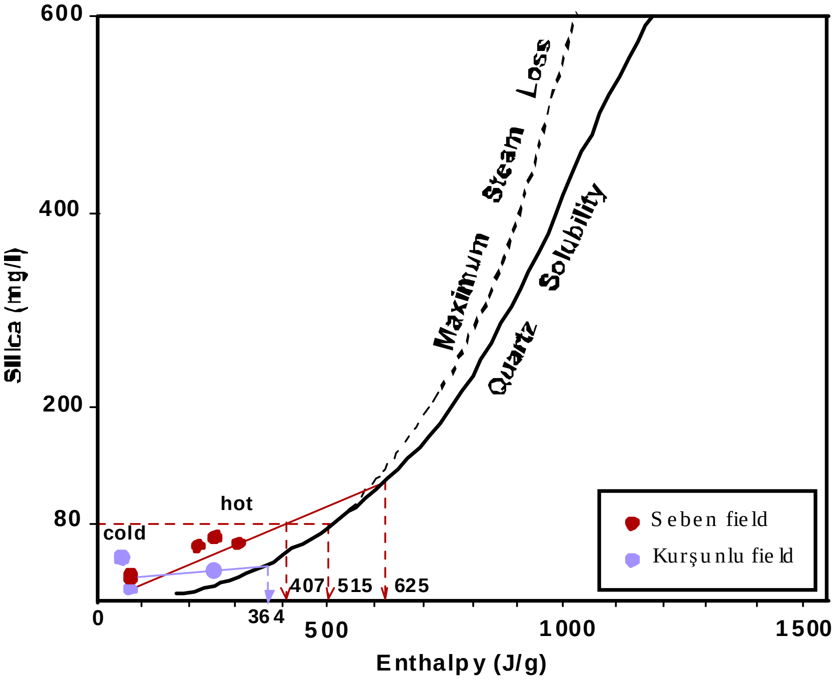

Figure 7. Enthalpy-silica mixing model for samples from Seben and Kurşunlu fields. Quartz solubility curves are from Fournier (1977).

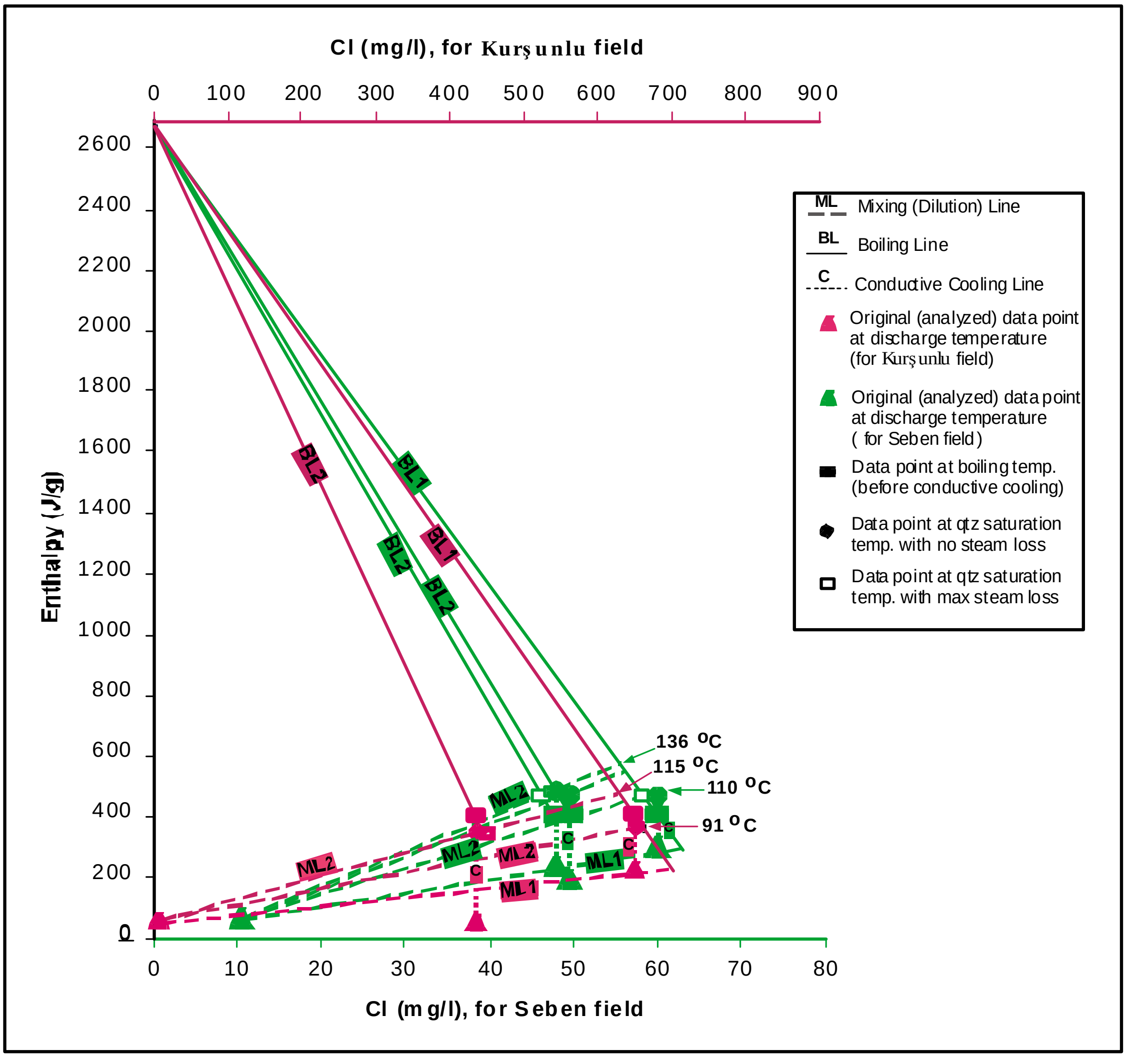

Figure 8. Enthalpy-chloride mixing model for samples from Seben and Kurşunlu.

This temperature estimate is based on the assumption that the steam formed during a possible boiling process did not separate from the residual liquid before mixing with the cold water component. Alternatively, if a possible steam loss is assumed to have occurred prior to mixing, then taking the enthalpy of water at the temperature of steam formation as 407 J/g (boiling at 97 °C at the elevation of Seben), the initial enthalpy is found as 515 J/g, which corresponds to a reservoir temperature of 122-123 °C.

For Kurşunlu field, since the silica content of the cold water is higher than those of the mineral water and the hot water (implying a possible silica precipitation for the latter two samples, either before or after sampling), the mixing line is drawn between the mineral water and the hot water samples. The line intersects the solubility curve at an enthalpy of 364 J/g which corresponds to a reservoir temperature of 87 °C which is possibly an underestimate because of the inferred silica precipitation.

In chloride-enthalpy model (Figure 8), possible reservoir temperatures were estimated via testing a number of likely scenarios: i) boiling of deep reservoir fluid followed, in turn, by conductive cooling and mixing, ii) mixing followed, in turn, by boiling and conductive cooling, and iii) mixing followed by conductive cooling (with no boiling).

For this purpose, as a first step, the original data points at discharge temperatures are projected upwards to 97 °C (boiling temperature at the elevation of Seben and Kurşunlu) assuming conductive cooling to discharge temperatures following boiling (dashed lines, marked as C in Figure 8, represent conductive cooling). Of these points, the ones with the highest enthalpy and the highest Cl content are then connected to the point with 2670 J/g and 0 mg/l Cl^- (representative of steam at 97 °C) producing the boiling lines (BL1). Since the mixing lines (ML 1) drawn through the original data points intersect the boiling lines (BL1) at temperatures lower than the boiling temperature (97 °C), the first scenario is proven to be invalid.

Regarding the second scenario (the hot samples representing the products of adiabatic and subsequent conductive cooling of mixed waters) all the data points at boiling temperatures are connected to the point representing the steam phase, and boiling lines (BL2) are produced. On these boiling lines are marked the temperatures estimated through the use of the quartz geothermometer with maximum steam loss. The data points obtained in this way are then joined to the cold water sample, producing the mixing lines (ML 2). The intersections of these mixing lines with the boiling lines yield reservoir temperature estimates ranging between 110 °C - 136 °C for Seben. For Kurşunlu, on the other hand, since quartz (with maximum steam loss) temperature is lower than 97 °C (see also Figure 5) (possibly owing to silica precipitation mentioned in silica-enthalpy model), the second scenario seems to be inappropriate.

In order to test the third scenario (the hot samples representing mixed waters which cooled conductively to discharge temperatures without any adiabatic cooling), the original data points (at discharge temperatures) are projected upwards to temperatures obtained from the quartz geothermometer with no steam loss. The mixing lines drawn through these data points coincide with the ones drawn for second scenario (i.e., ML 2). The intersections of these mixing lines with the boiling lines yield reservoir temperature estimates ranging between 110 °C - 136 °C for Seben, and between 91 °C - 115 °C for Kurşunlu field. These temperature ranges similar -more or less- to the quartz temperature estimates for the respective fields.

6. ASSESSMENT OF SCALING POTENTIAL

In an attempt to assess the scaling potential during the possible development of the geothermal fields, saturation index calculations (at discharge temperatures) were performed using the program WATSPEC (Wigley, 1977) As can be seen from Figure 9, all hot waters are likely to precipitate silica and three of them, namely Kurşunlu, Efteni and Reşadiye samples, are likely to precipitate calcite. In fact, calcite scaling at the production well and widespread travertine deposition around the springs is observed in Kurşunlu and Reşadiye fields, respectively.

7. CONCLUSIONS

1) Except Bolu and Mudurnu samples which are Ca-Mg-SO_4 and Ca-HCO_3 type, respectively, all the hot waters along the NAFZ are Na-HCO_3 type waters.

2) Mixing with cold waters and conductive cooling seem to be the major subsurface processes controlling the chemical composition and temperature of the hot waters in Kurşunlu, Seben and Mudurnu geothermal fields.

3) Quartz geothermometers seem to yield the most representative estimates for reservoir temperatures and are more or less supported by the temperatures obtained from silica -enthalpy and chloride-enthalpy mixing models for Seben and Kurşunlu fields. In this respect, the possible reservoir temperatures range from 88 to 115 °C for Kurşunlu, 85 to 88 °C for Bolu, 143 to 150 °C for Efteni, 77 to 86 °C for Mudurnu, 110 to 149 °C for Seben, 97 to 99 °C for Reşadiye and 67 to 72 °C for Gözlek fields.

4) Efteni and Seben fields are more promising for geothermal energy development, temperatures being high enough for conventional electric generation. In Kurşunlu, Mudurnu and Reşadiye fields, the estimated reservoir temperatures appear to be suitable for binary fluid electric generation. Direct applications such as balneology, greenhouse or space heating are the possible utilization areas for almost all the fields. Since all the hot waters are oversaturated with respect to silica, and Efteni and Reşadiye waters are oversaturated also with respect to calcite, necessary precaution must be taken against possible scaling problems during geothermal energy development and utilization.

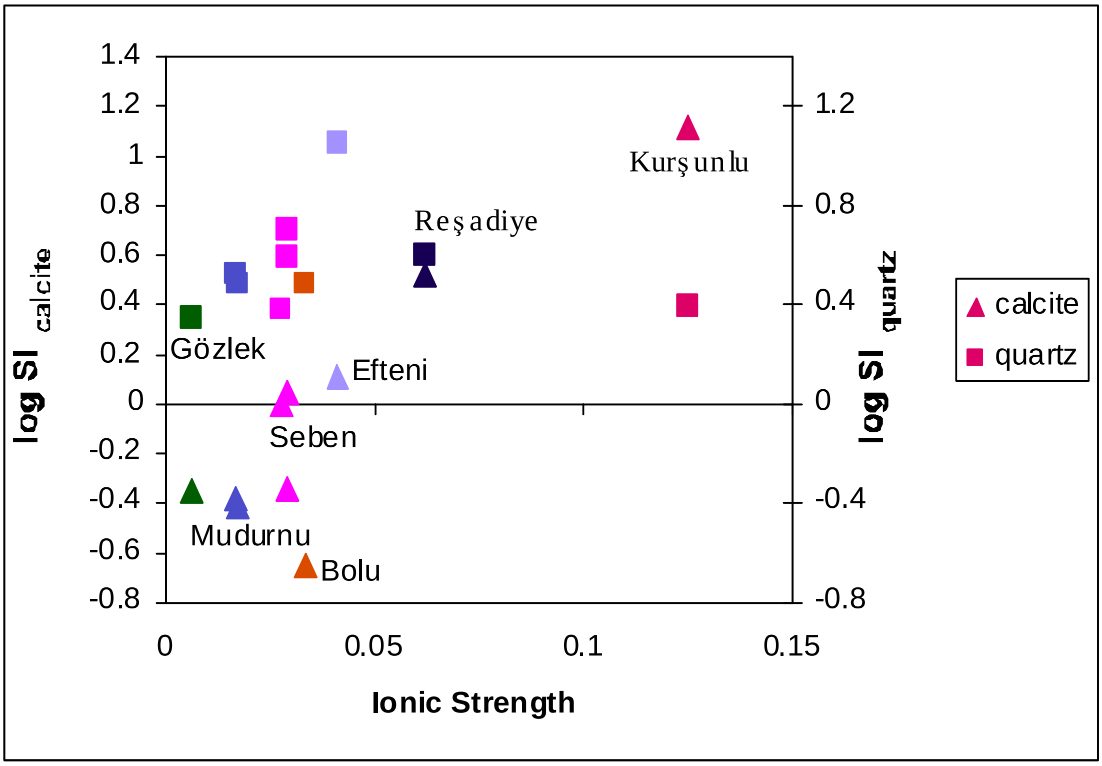

Figure 9. Saturation index vs. ionic strength diagram for the hot waters.

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