

Active Geothermal Systems in SİMAV and Environs within the Menderes Massif, Western Anatolia, Turkey

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ABSTRACT

Simav geothermal field, one of Turkey's most important fields, is located in Simav graben system within the Menderes Massif in Western Anatolia, Turkey. This is on the eastern part of the graben and approximately 4 km north of Simav town and on the NE edge of the Simav plain, which is separated from the mountain by a high and steep escarpment. The plain covers an area of about 70 km² and is at an altitude of about 780 m above sea level and lies on latitude 39° 5' 23" N and longitude 28° 58' 46" E. The thermal waters of Simav can be classified as Na-HCO₃-SO₄ type water with the dominant cations in increasing order of Na+>Ca>Mg while the anions are HCO₃>SO₄>Cl. The Cl-SO₄-HCO₃ ternary diagram shows that the waters are peripheral/immature and more likely related to groundwater heated by steam from deeper reservoirs. Quartz, aragonite, calcite and chalcedony are oversaturated at discharge temperatures while at a recomputed temperature according to the reservoir composition, only quartz, dolomite and chalcedony are oversaturated. The silica geothermometer shows reservoir temperatures between 83 and 182°C. The Na-K-Ca-Mg correction cation geothermometer give reservoir temperatures close to the measured reservoir temperature on site in Eynal which is between 148 and 163°C. The waters plot along the meteoric water line suggesting the source from local meteoric water and are rich in ¹⁸O. This situation points to the existence of fluid-interaction in the system and/or boiling due to the high temperatures in the reservoir.

1. INTRODUCTION

Nowadays, many countries are shifting focus and attention to renewable energies. Renewable energy is sustainable because the resources are used in a manner that provides ongoing energy to meet the needs of the current population, without compromising conditions for future generations. Geothermal energy is one of the many renewables available. Geothermal fields are found throughout the world in a range of geological settings, and are increasingly being developed as an energy source. Each of the different types of geothermal system has distinct characteristics which are reflected in the chemistry of the geothermal fluids and their potential applications. However, they all have in common a heat source at a few kilometers depth, and it is this which sets water, present in the upper sections of the Earth's crust into convection. Simav geothermal field, one of Turkey's most important fields, is located in Kütahya's Simav graben system within the Menderes Massif in Western Anatolia (Figure 1). This is on the eastern part of the graben and approximately 4 km north of Simav town and on the NE edge of the Simav plain, which is separated from the mountain by a high and steep escarpment (Figure 2). The plain covers an area of about 70 km² and is at an altitude of about 780 m above sea level and lies on latitude 39° 5' 23" N and longitude 28° 58' 46" E. The thermal water produced from this field is used for heating of the residential houses in the city (about 7000) while there is an ongoing effort in utilizing it for power generation.

The Purpose of this study is to understand the formation and development history of the geothermal waters by hydrogeological, hydrogeochemical and isotope geochemical methods and to determine the water types in the geothermal area.

2. GEOLOGIC SETTING

The Simav geothermal field is located in the eastern part of Simav graben, approximately 4km north of Simav town and on the NE edge of the Simav plain, which is separated from the mountain by a high and steep escarpment (Figure 2). The plain covers an area of about 70 km² and is at an altitude of about 780 m asl. In contrast, Simav Mountain, which is a horst structure, located to the south of the plain, reaches an altitude of 1,780 m above sea level.

The stratigraphic sequence of the formations in the Simav region is given in (Figure 3). Paleozoic metamorphic rocks are located at the base of the rock strata in the region. These rocks form the mountains that border the graben on both sides, and outcrop frequently in these mountains. Also, it is known that under the graben, these rock units are underlain by younger sedimentary rocks. The metamorphic rocks are covered by a layer of lower Mesozoic rocks and Jurassic carbonates that have not been metamorphosed, which also overlay the metamorphites in the Simav horst to the south of the graben as well as in the relatively lower Akdağ horst to the north. These rocks are overlain by volcanic rocks and lake sediments of Miocene age that were deposited in the graben along a NNE-SSW axis or formed in relation to those grabens. These formations appear on the Simav horst to the south of the graben as well as on ridges of the arm to the north of the graben, which has risen to a lower altitude. These are followed by younger formations which precipitated or formed together with the Simav graben or at a later time (Akdeniz and Konak, 1979). These are spread out over the graben interior areas, which have been downthrown significantly compared with the horsts on both sides of the Simav graben. The coarse-grained terrestrial sediments, basaltic lava deposits and thick alluvium have created a layer in the graben that is hundreds of meters thick (Öngür, 2004). Based on the existing wells drilled in the region, the fractured reservoir rocks producing hot fluids in the field largely consist of Naşa Basalt, Simav metamorphics and Mesozoic limestones, while the cap rock consists of Tertiary strata of volcano-sedimentary rock. In extensional tectonic regimes like the Basin and Range province and the Anatolia Belt of western Turkey, extensional detachments have created favorable structures for geothermal occurrences. Three crustal segments, namely central core, southern and northern sub-massifs, differing in structure and cooling history have been

identified in Menderes Massif of western Turkey by Ring et al. (2003). The Simav detachment, formed later, reactivated the Eocene Cyclades-Menderes thrust and its initial movement was synchronous with the intrusion of Eğrigöz granites (Ring et al., 2003). After Miocene, western Anatolia underwent the extensional regime that helped build the actual form. This process produced the Simav graben, which has an asymmetric structure. The southern part of the graben is limited by the Simav fault, which is roughly extended in west-east direction for more than 80 km and separates Simav Mountain from Simav plain.

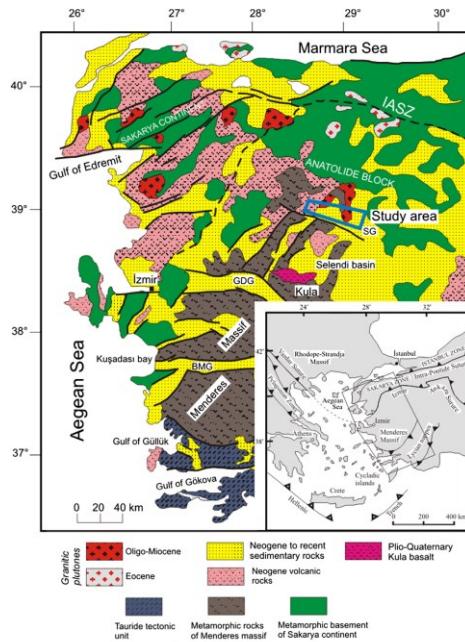


Figure 1: Main tectonics and geological units of western Anatolia. IASZ: İzmir-Ankara Suture Zone, SG: Simav graben, DG: Gediz graben, BMG: Büyük Menderes graben (modified from Yilmaz, 2000)

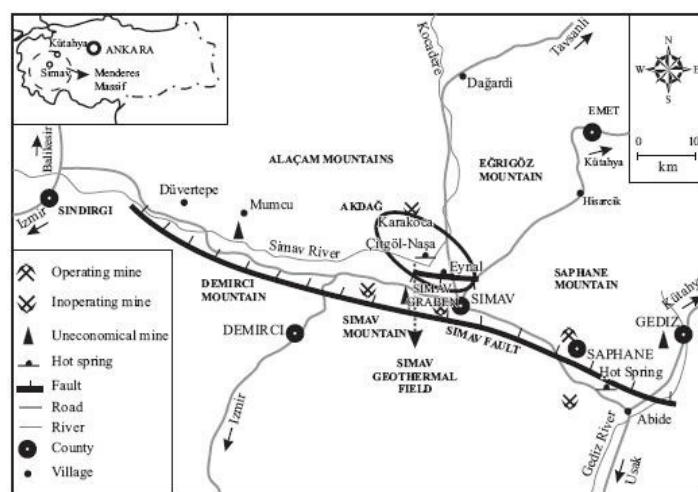


Figure 2: Location map of the study area (modified from Öygür and Erler, 2000).

3. HYDROGEOLOGY, HYDROGEOCHEMISTRY AND ISOTOPE GEOCHEMISTRY

3.1 Hydrogeology

Joints and faults resulting from neotectonic activity caused the developments of secondary porosity and high permeability in limestone and marble. In the study area, three (3) reservoir rocks were determined (Figure 4).

I. Reservoir rocks: The Nasa basalt pinching out in quaternary unit is the shallow reservoir rock. The Nasa basalt and the Toklulgöl formation cover an area of 84 km² in the study area. The Nasa basalt covered by alluvium and Eynal formation, geothermal fluid production is active in C-1, C-2 (abandoned C-3, C-4, C-5) and N-1, N-2 wells. In addition, hot water has been produced from the first reservoir rocks in some of the other boreholes. The highest temperatures in first reservoir rock were measured at 85m of depth in C-1 well to be 105°C (Bayram and Şimşek, 2005).

II. Reservoir rocks: The Budakan limestone and the Arikaya formation having secondary porosity and permeability are the second reservoir rocks. These formations crop out in an area of 25 km². These formations have longer lateral extension and are located deeper than first reservoir rocks. Therefore higher temperatures were obtained.

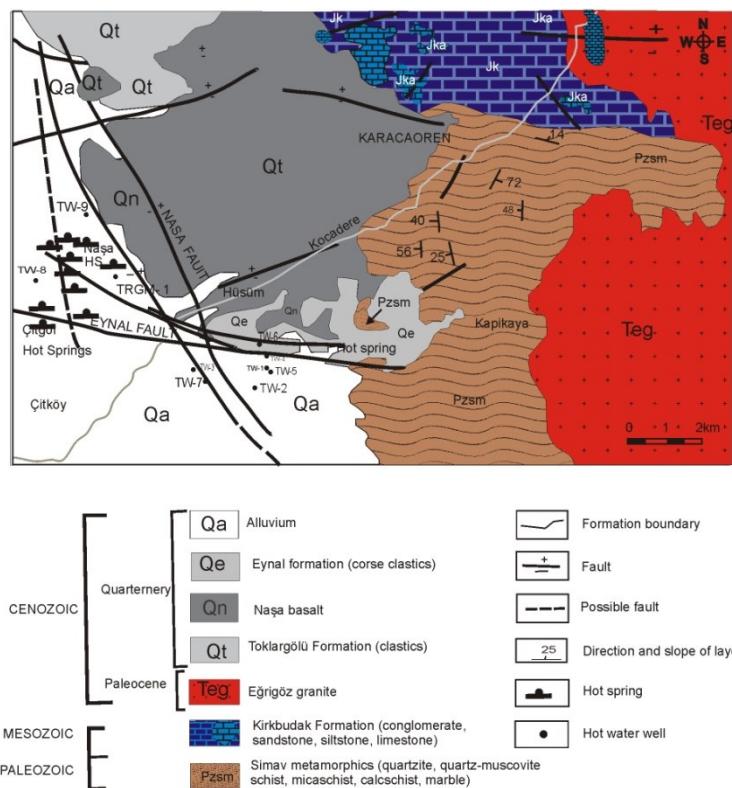


Figure 3: Geological map of the study area (modified from Akkuş et al., 2005).

Hot waters from EJ-1, EJ-2, E-2, E-3, E-4, E-5, E-6, E-7, E-8, and E-9 are drawn from this reservoir. The highest temperature of 162.47 °C was measured from EJ-1 well (Bayram and Şimşek, 2005).

III. Reservoir rocks: It is possible to consider the presence of third reservoir rock depending on the interbedding of cover and reservoir rocks. The Balıkbaşı formation crops out in an area of 6 km² in the study area. It comprises of secondary porous and permeable marble and underlines the Sarıcasu formation having cover rock characteristics. EJ-1 and EJ-2 wells yield hot water at this reservoir (Bayram and Şimşek, 2005). In the study area, three sealing cap rocks having impermeable characteristics were determined.

I. Cap rocks: The Eynal formation over the Nasa basalt contains impermeable clayey level in places. In wells around the Nasa and Çitkoy thermal springs, after alluvium, impermeable levels of formations were cut. This shows that it has characteristics of cap rock. It crops out in an area of 2 km² in the study area.

II. Cap rocks: The Akdag volcanic rocks, the Civanadag tuffs and the Kızılık formation form a thick cap rock. All these units cover an area of 140 km² in the study area. The temperature is raised to 162 °C due to the presence of these cap rocks. Meanwhile, a temperature of 105 °C was measured in the reservoir under the first cap rock.

III. Cap rock: The Sarıcasu formation has lateral and vertical transition with the third reservoir rocks. It crops out in an area of 19 km² in the study area.

3.2 Water-rock interaction

In Simav and environs, the rocks are altered due to intensely water-rock interaction. The hydrothermal alteration of the host rocks can be recognized by a distinct color change of the thermal field. During the realization of this study, we do not have access to any rock sample from drilling cores. In comparison, surface geological investigations indicate hydrothermal alteration minerals such as alunite (Burçak et al., 2007) and kaolinite along the Simav fault between Düvertepe and Şaphane. In summary, the primary alterations minerals are chlorite, albite, K-feldspar, epidote, muscovite, illite, and montmorillonite. From these minerals, the ones that are most notable with respect to hydrothermal alteration are chlorite, K-feldspar, illite, montmorillonite, and epidote (Palabıyık and Serpen, 2008). The epidote generally occurs in thermal fields with temperatures between 200 and 250 °C (Bird, et al., 1984). On the other hand, illite is generally observed over 180 °C (Browne, 1996). Finally, it might be concluded that the Simav thermal field is high-temperature and high sulfidation area with suitable alteration mineralogy.

3.3 Hydrogeochemistry

The thermal waters were collected from drilled wells with only one from hotspring. Locations of the sampling points (TW) are shown in Figure 3. Based on the conducted field studies, a total of 10 samples were collected for each analysis. In-situ and hydrogeochemical analysis were carried out on these samples. The in-situ analyses such as temperature, pH, EC, TDS, dissolved oxygen, Eh and alkalinity were conducted on the field. The hydrogeochemical analyses were done at Galtek Chemical Industrial and Trading Ltd., Istanbul, Suleyman Demirel University, Department of Environmental Engineering and Metrohm (34330, Levent-Istanbul). The results are presented in Bello (2012). In summary, the temperature ranges from 61.6 - 91 °C, pH is between 7.40 and 8.78 and electrical conductivity ranges from 1620 - 2990 µS/cm. The detailed results are given in Bello (2012). The following cations and elements, Na^+ , Ca^{2+} , Mg^{2+} , K^+ , Pb , SiO_2 , Zn , Al , Cr , Cu and As were analyzed using ICP-OES and ICP-MS, while the following anions, F^- , Br^- , Cl^- , SO_4^{2-} , NO_3^- , NO_2^- and PO_4^{3-} were analyzed using Ion-chromatography (Bello. 2012). The HCO_3^- and CO_3^{2-} were calculated from the alkalinity measurements on the field. For the examination and geochemical analysis

of the results, Aquachem v.3.7 (Waterloo Hydr., 1999), Liquid analysis geochemical plotting spreadsheet (Powell and Cumming, 2010), and Solveq (Reed and Spycher, 2001) were used to evaluate the hydrogeochemical characteristics of the study area. The hydrogeochemical analyses are presented in Bello (2012).

The results from the hydrogeochemical analyses of the samples from Simav region were evaluated using AquaChem v.3.7 (Waterloo Hydro., 1999) and Liquid analysis spreadsheet (Powell and Cumming, 2010). Diagrams such as piper, schoeller and ternary were prepared to graphically illustrate the hydrochemistry of the water samples and to determine the type of water present in the geothermal system of Simav and environs. According to piper diagram in Figure 5, the thermal waters in Simav region can be classified as Na-HCO₃-SO₄ type water while sample TW-10 from Ilicasu kaplicalari is classified as a Na-Ca-SO₄-HCO₃. Using schoeller diagram (Figure 6), the waters from the Simav region can be classified as Na+K > Ca > Mg according to the dominant cations and as HCO₃> SO₄> Cl according to the dominant anions.

The Cl-SO₄-HCO₃ ternary diagram is used to classify geothermal fluids on the basis of the major anion concentrations (Giggenbach, 1988). It helps to discern immature unstable waters and gives an initial indication of mixing relationships or geographic groupings. The Cl-SO₄-HCO₃ plot of the samples from the study area shows that the waters plot on the peripheral water region (Figure 7) and it is a bicarbonate water due to the predominant plots on the bicarbonate vertex of the ternary diagram. It shows that the water is more likely related to groundwater heated by steam from deeper reservoir. Hence, it may not give the best predictive result of the reservoir temperature using geothermometer.

The Na+K-Mg-Ca ternary diagram (Figure 8) of the study area shows that the cation is predominantly Na+K as the plots converge at the Na+K corner. This is expected because Na⁺ contents of water increase with temperatures while Ca²⁺ and Mg²⁺ contents decrease. Hence the low values of Ca²⁺ and Mg²⁺ in the geothermal waters of the study area. However, sample TW-10 has a high Ca²⁺ content which is suspected to have moved through a calcite bearing rock. This is true considering the presence of limestone in the area in which the sample was taken.

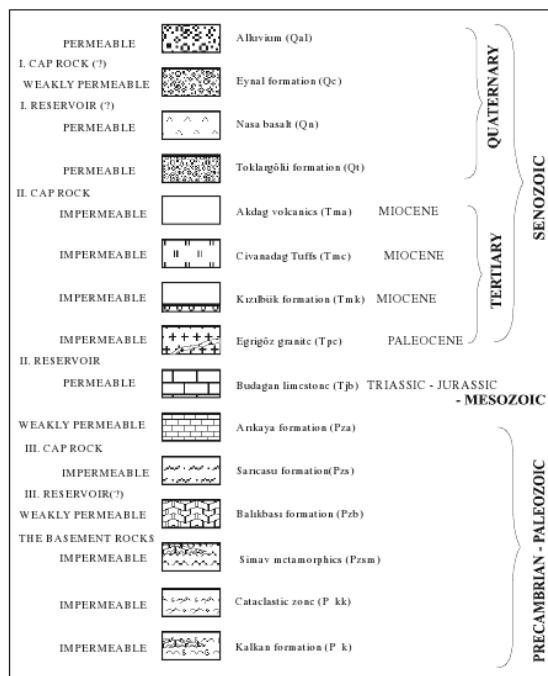


Figure 4: Hydrogeological Characteristics of the rock units (modified from Bayram and Şimşek, 2005).

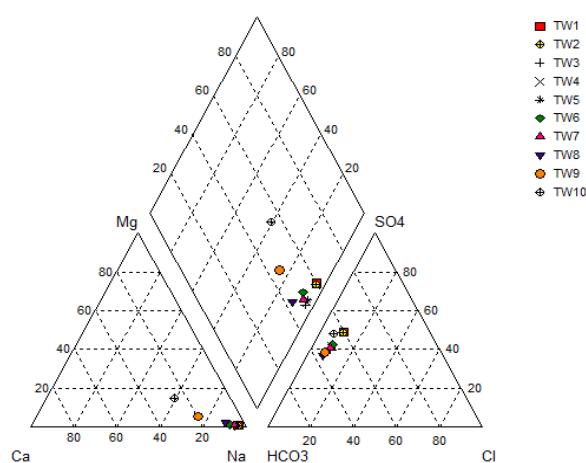


Figure 5: Piper diagram of thermal waters from the study area

The saturation indices of some carbonates (commonly calcite, aragonite and dolomite; minority siderite and magnesite), Sulphate (commonly gypsum and anhydrite) and silica (commonly quartz and chalcedony) minerals help us to estimate which one of these minerals may precipitate during the extraction and use of the geothermal fluids. These calculations are useful in predicting the presence of reactive minerals and estimating mineral reactivity in a groundwater system (Deutsch, 1997; Gemici and Tarcan, 2002). Saturation indices also help us to evaluate the chemical equilibrium between fluid and rock in a geothermal system. This is accomplished by gathering information about the solubility of minerals in rocks that have undergone hydrothermal alteration and about the activity of the mineral type in the solution. Because of the large number of ions, ion-pairs and complexes in the solution, generating the saturation index for each type as well as activities requires the use of a software program. For this exercise, Solveq (Reed and Spycher, 2001) was used to compute the saturation index. The saturation indices of the thermal waters were calculated at the discharge temperature as well as simulation with increase temperature and measured pH values. Quartz, aragonite, calcite and chalcedony are oversaturated at discharge temperatures while at a recomputed temperature according to the reservoir composition, only quartz, dolomite and chalcedony are oversaturated. According to this saturation indices, scaling of carbonate minerals is expected for the geothermal waters and this coincides with field observation as waters from deep wells cause scaling during extraction. Inhibitors are employed in the prevention of scaling in the drill holes.

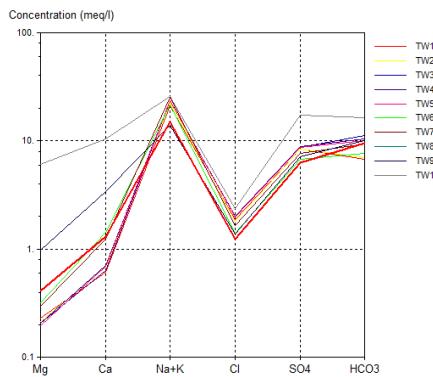


Figure 6: Schoeller diagram of the thermal waters in the study area.

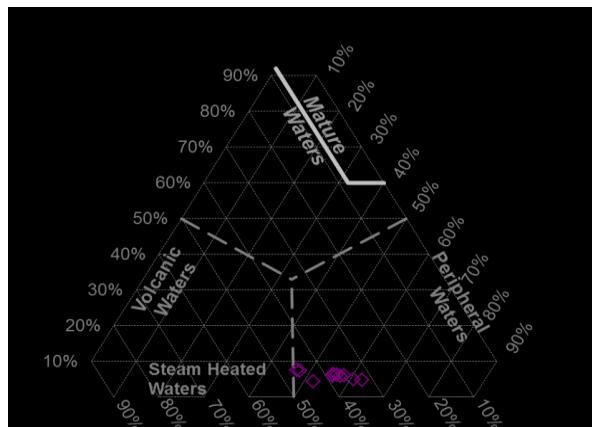


Figure 7: Cl-SO₄-HCO₃ ternary diagram showing that the waters are immature.

The hydrogeochemical results of the geothermal waters from the study area were evaluated using both silica and cation geothermometers in order to understand the reservoir temperature of the geothermal field. The results of the geothermometers are given in Bello (2012).

The quartz (conductive and adiabatic) geothermometers for Eynal area (TW1-TW7) calculated the reservoir temperature to be between 191 – 231 °C while Çitgöl (TW8), Naşa (TW9), and İlicasu kaplıcaları (TW10) are 163 -174 °C, 156 -166 °C and 203 -225 °C respectively. For α -cristobalite, β -cristobalite and amorphous silica, proposed by Fournier (1977), in Eynal region, the reservoir temperatures gave values between 83 – 182 °C and Çitgöl, Naşa, with İlicasu kaplıcaları gave between 50 - 124 °C, 43 – 115 °C and 98-175 °C respectively. The Na-K-Ca-Mg correction cation geothermometer gave reservoir temperatures close to the measured reservoir temperature on site in Eynal. The calculated temperature for Eynal is between 148-163°C. The other cation geothermometers gave values that are too high (Bello, 2012).

The Na-K-Mg^{1/2} ternary diagram was proposed by Giggenbach (1988) as a method to make a clear distinction between the thermal waters that are suitable for the estimation of reservoir temperature by the application of solute geothermometers. The waters from Simav geothermal field fall in the immature waters (Figure 9). Waters from Eynal (TW1-TW7) are located close to the boundary of partially equilibrated waters. The other three samples (TW8-TW10) fall closer to cold groundwaters suggesting that they have mixed with a greater portion than the Eynal thermal waters.

3.4 Isotope geochemistry

The isotope geochemistry of a geothermal system provides information about the origin, dating and residence time of the geothermal fluid, the physical processes to which the water is subjected, the fluid-rock interaction and the reservoir. For this study,

the isotopic data from Bayram and Şimşek (2005) were used in assessing the origin of the geothermal waters from the study area (Bello, 2012). The geothermal waters from the study area plot along the meteoric trend line suggesting local meteoric water (Figure 10). Furthermore, they are enriched in $\delta^{18}\text{O}$. This situation points to the existence of fluid-interaction in the system and/or boiling due to the high temperature in the reservoir. Also, the change of δD content in the waters may indicate that the system is fed by waters from a high altitude or come from long distance.

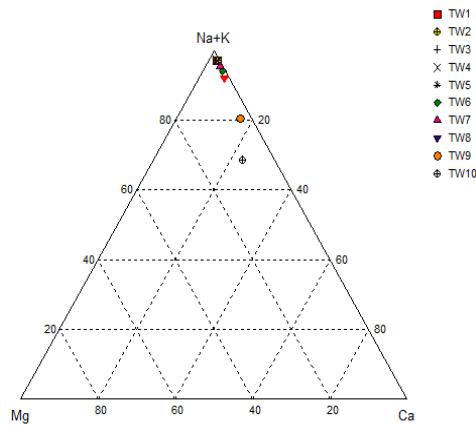


Figure 7: Na+K-Mg-Ca ternary diagram showing high Na+ contents in the thermal waters of Simav and environs.

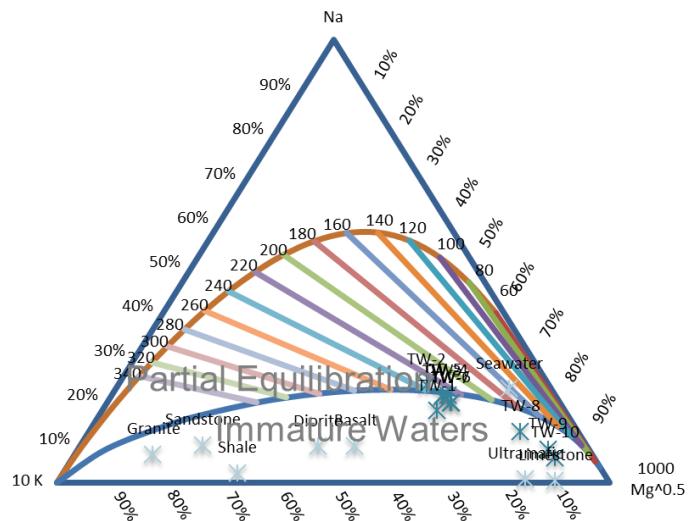


Figure 9: Distribution of the thermal waters from the study area in the Na-K-Mg $^{1/2}$ ternary diagram.

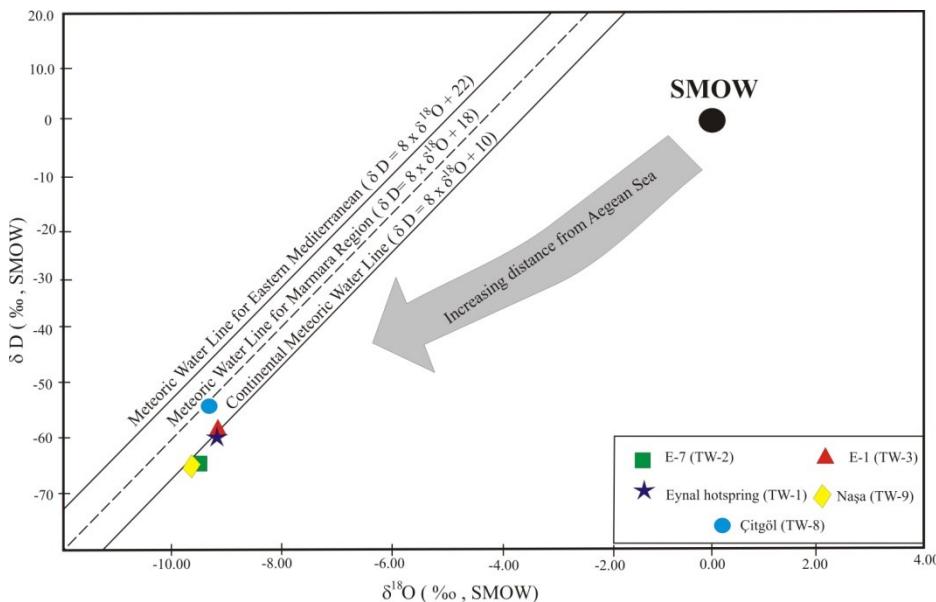


Figure 10: δD versus $\delta^{18}\text{O}$ of the geothermal waters in Simav and environs.

4. DISCUSSION

4.1 Hydrogeological modeling of the geothermal systems in Simav and environs

Several hot springs, ranging in temperature from 61.6 to 91 $^{\circ}\text{C}$, emanate from alluvium along the northern margin of the basin, where sediments are juxtaposed against Naşa basalt along a complex, anastomosing part of the S-dipping antithetic fault system. Several of these faults are marked by Quaternary fault scarps. The main E-W trending line of hot springs in the Eynal area is situated in the hanging wall of this anastomosing normal fault system. There is reason to believe that there exists a high-temperature system ($>180\ ^{\circ}\text{C}$) at depth because of the discovery of opaline sinter at the surface along some of the hot springs. Existing wells penetrate to 958 m, but the main reservoir may not be discovered yet. This reservoir may lie in the metamorphic basement and partly in the Miocene igneous rocks (Faulds et al., 2010).

The geothermal activity at Eynal may be primarily controlled by multiple fault intersections within the anastomosing S-dipping normal fault system, whereby highly fractured steeply dipping conduits have provided pathways for fluid circulation. At depth, the waters react with heated rocks. The CO_2 , SO_2 , HCl and H_2S that escaped from the magma reached the geothermal water reservoir where equilibrium is reached between altered rocks and fluids. Thus the thermal waters escape into tectonic zone of weakness, namely the Simav fault, as hot springs to the surface (Figure 11).

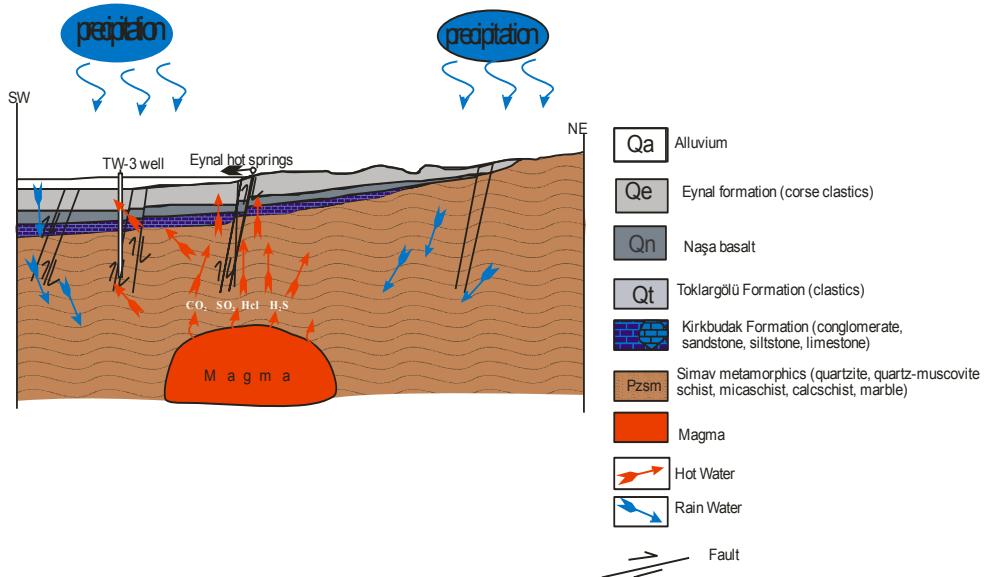


Figure 11: A simplified model of the geothermal systems in Simav and environs.

4.2 Relationship between tectonics and heat Source of the geothermal Systems in Simav and environs

Turkey is known to have many low to moderate temperature geothermal resources (Serpen and Mihcakan, 1999; Palabiyik and Serpen, 2008) and most of these resources are related to important fracture systems. The major geothermal systems of western

Turkey are all structurally similar geothermal occurrences. A localized extensional tectonic regime prevails in western Anatolia where the lithospheric stresses are mostly related to the continental collision of Alpine-Himalayan zone. Western Anatolia is characterized by east-west trending mountain range, and deep sediment filled valleys. The region experienced a north-south shortening until the beginning of the late Miocene. At the beginning of the Tortonian, the region experienced an extension, and the partially melted crust began stretching to form a thin and a brittle crust (Yilmaz, 1989; Alptekin et al., 1990; Gemici and Tarcan, 2002). There are a few E-W trending grabens in Western Turkey. Most of the important geothermal areas of Turkey are located in the rims of these grabens. Simav graben is one of them and formed by WNW-ESE trending and north-dipping fault. The Simav graben is a Pliocene-Quaternary structure with a distinct topographical depression, extending for about 150 km. The graben cuts the NE-SW trending Demirci, Selendi and Akdere basins and is regarded as one of the latest products of N-S extensional tectonics, in contrast to the Aegean grabens that began to develop during late Oligocene-Early Miocene times (Seyitoğlu, 1997). The southern side of the Simav half-graben cut the Neogene basins and also the Simav detachment fault. Bozkurt et al. (2011) suggested an episodic Simav detachment fault activity between ca. 30 and 8Ma. The occurrence of volcanic rocks intercalated with sediments in graben-type structures, and extensional uplifting of the region shows that (Early to Middle Miocene) magmatism in Simav region took place under an extensional tectonic regime in a back-arc position.

The graben is bounded on the south by a major N-dipping normal fault that has accommodated several kilometers of normal slip and is referred to as the Simav fault. This fault is part of a large semi-continuous WNW to EW striking fault zone that extends across much of western Turkey and may have accommodated some strike-slip displacement. A system of S-dipping antithetic normal faults with much less displacement bounds the normal margin of the basin (Faulds et. al., 2010). The Simav fault penetrates very deep to communicate a deep heat sweep of naturally convecting meteoric waters in the metamorphic crust. Hochstein et al. (1990) pointed out that fracture zone systems, which are driven by higher than normal heat flow; occur in areas underlain by thinner continental type of crust (*i.e.*, systems in the Basin and Range tectonic province of USA and Menderes Massif of Turkey). An earlier theoretical study by Kassoy and Zebib (1978) also showed that fluid convection can occur in a narrow fracture zone which stands in a crustal environment with normal temperature. The Simav geothermal system is thought to be controlled by the active Simav fault and probably driven by higher than normal heat flow, 110mW/m² (Ilkisik, 1995; Palabiyik and Serpen, 2008), in the Aegean region of Turkey, and terrain-induced forced convection. With prevailing temperatures of about 160 °C at economic depths (less than 1 km) within the fracture zone reservoir, the Simav geothermal system resembles “the fracture zone systems with high temperatures at sweep base” described by Hochstein (1990).

4.3 Conclusions

Joints and faults resulting from neotectonic activity in the study area caused the developments of secondary porosity and high permeability in limestone and marble. Four reservoir rocks for three different reservoirs are determined in the study area. The reservoir rocks are Naşa basalt, Budağan limestone, Arikaya formation and Balıkbaşı formation, all hosting the geothermal waters in the study area. Three cap rocks were also identified in the study area and they are the Eynal formation, Akdağ and the Sarıcasu formation.

The geothermal waters have surface temperatures between 61.6 and 91 °C and are mostly Na-HCO₃-SO₄ type water while sample TW-10 from Ilicasu hot springs are classified as a Na-Ca-SO₄-HCO₃. They can also be classified as Na+K>Ca>Mg according to the dominant cations and as HCO₃>SO₄>Cl according to the dominant anions with Schoeller diagram. The Cl-SO₄-HCO₃ plot of the samples from the study area shows that the waters plot on the peripheral water region and it is a bicarbonate water due to the predominant plots on the bicarbonate vertex of the ternary diagram. It shows that the water is more likely related to groundwater heated by steam from deeper reservoir. Hence, it may not give the best predictive result of the reservoir temperature using geothermometer.

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