Active geothermal systems in the rift zone of the Büyük Menderes, Western Anatolia, Turkey

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Abstract

Hydrogeological, hydrogeochemical, and isotope geochemical data of the thermal waters of Kızıldere, Salavatlı, and Germencik in the rift zone of Büyük Menderes were studied. The metamorphic and sedimentary rocks in the fields are altered intensively. The hydrothermal alteration is distinguished by phyllic, argillic, silicic ± haematitization, and carbonatization zones. The surface temperatures of the waters range from 30 to 99 °C whereas the geochemical thermometers indicate a reservoir temperature between 162 and 242 °C. The Na-(SO_4)-(Cl)-HCO_3 type thermal waters show meteoric origin due to isotopic ratios of δ^2H versus $\delta^{18}O$.

Keywords: Geothermal systems, Büyük Menderes, Turkey.

Introduction

The tectonic position of the eastern Mediterranean area between the Eurasian and African plates is controlled by the Anatolian and Aegean microplates. The plate tectonic development results in the uplift of the Menderes Massif due to compressional tectonic features from Oligocene to Miocene. From Early to Middle Miocene, the continental rift zones of the Büyük Menderes, Gediz, and Küçük Menderes were formed in E-W directions by extensional tectonic features. One of these is the rift zone of the Büyük Menderes which is represented by a great number of geothermal hot springs, i.e. Kızıldere, Salavatlı, and Germencik located from Denizli in the eastern part to Kuşadası at the Aegean Sea in the western part within the Menderes Massif (Figs. 1 and 2) [1], in connection with volcanic activity from Middle Miocene to recent. These geothermal waters are related to faults which strike NW-SE and NE-SW, diagonal to general strike of the rift zone of the Büyük Menderes, and are generated by compressional tectonic stresses and uplift between two extensional rift zones [2, 3, 4, 5]. In addition to heat flow anomalies in the rift zone of the Büyük Menderes [6], there is very intensively volcanic activity which is represented by various localities of a great number of calkalkaline toward to acidic volcanic rocks and range from Middle Miocene to 18.000 a in age [4]. The volcanic rocks are products of continental crust based on isotope analyses of $\delta^{87}Sr/\delta^{86}Sr$ and $\delta^{144}Nd/\delta^{143}Nd$ and can be considered as heat source for the heating of the of thermal waters in the rift zone of the Büyük Menderes and elsewhere. Moreover, the geothermal gradients may contribute to heat the thermal waters in the reservoir consisting of limestone, marble, quartzite, and gneiss.

The aim of this paper is (i) to give a comprehensive overview and present hydrogeological, hydrogeochemical and isotope geochemical data of the thermal waters in the rift zone of the Büyük Menderes in combination with interpretation the origin and evolution of the thermal waters in the study area.

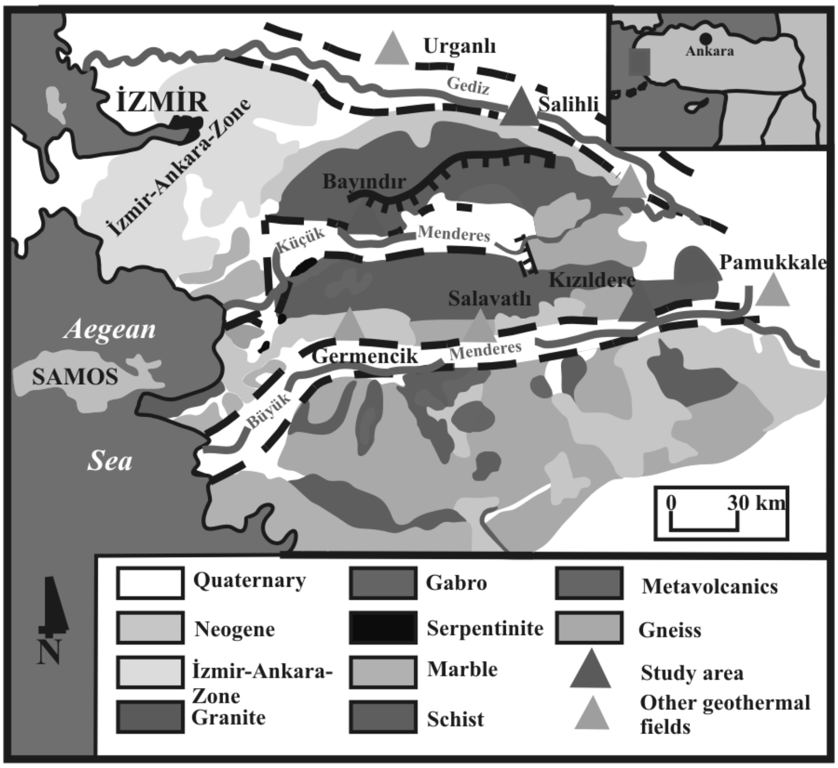

Fig. 1: Geologic setting of the Menderes Massif and location map of the studied thermal fields of Kızıldere, Salavatlı, and Germencik in the rift zone of the Büyük Menderes.

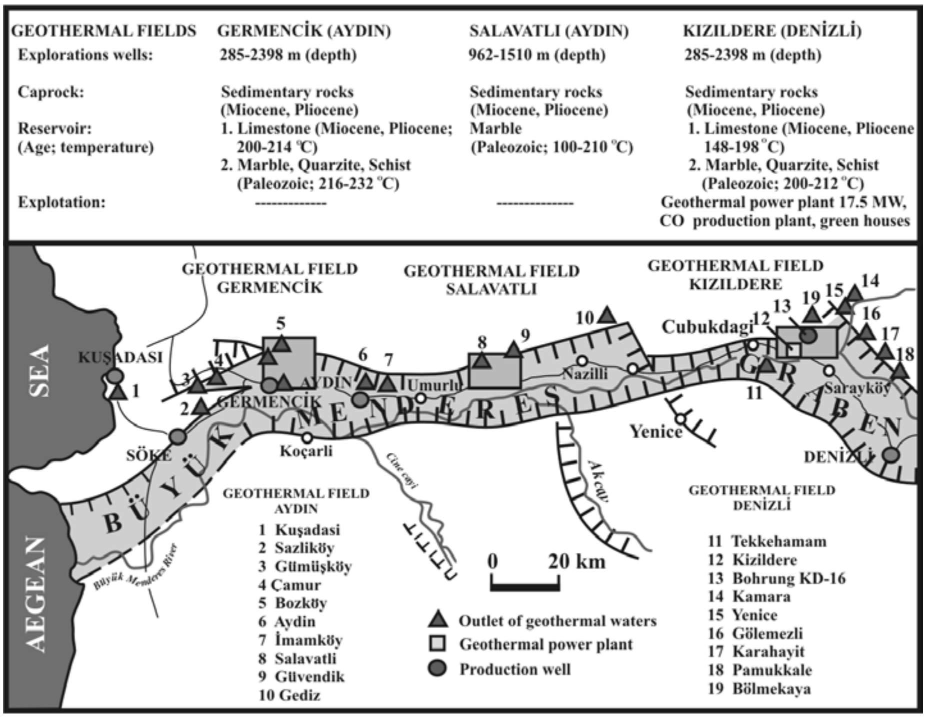

Fig. 2: Distribution of the thermal fields in the rift zone of the Büyük Menderes. Modified from [7].

Geologic setting

The metamorphic rocks of the Menderes Massif are (i) Precambrian to Cambrian core series consisting of high-grade shists, gneisses, granites and metagabbros and (ii) Ordovician to Paleocene cover series composed of mica shists, phyllites, metaquartzites and metagabbros (Fig. 1). In Cambrian, the first metamorphism in the Massif (M1) took place under amphibolite to granulite facies conditions affecting the core series intensively [8]. The core and cover series encountered a second Variscan metamorphism (M2) in which Early and Middle Triassic leucogranites intruded. These plutonic rocks are distinguished by Zr age of 230-240 Ma [9] which can be considered as a Variscan event in the region. In Eocene, high-pressure metamorphism (M3) was generated under epidote-blue shist to eclogite facies conditions, and the last phase of main metamorphism (M4) developed in Late Eocene to Early Oligocene [8] and is overprinted by Barrowian-type metamorphism. These metamorphic rocks in the Menderes Massif are overlain by Neogene to Quaternary thick sedimentary rocks.

In connection with the evolution of the continental rift zones of the Massif, an intensively volcanism was generated from Middle Miocene to recent. The oldest volcanic rocks in the rift zone of the Küçük Menderes are distinguished by a Rb/Sr age of 15,0 ± 02 in Karaburç and a K/Ar age of 16,7 ± 0,5 Ma in Yenişehir and can be classified into Middle Miocene [4]. The youngest volcanism in the entire Menderes Massif is characterized by the Late Pliocene volcanic rocks of Denizli and Söke in the rift zone of the Büyük Menderes [10] and the volcanics of Kula with an age ranging from 7,5 Ma to 18.000a [11]. Finally, the volcanic rocks can be considered as heat source for the heating of thermal waters in the rift zone of the Büyük Menderes.

The thermal field of Kızıldere with nine (9) production wells to a depth down to 2260 m and a reinjection well to a depth down to 1384 m is located in the north of the eastern part of the rift zone of the Büyük Menderes (Figs. 1 and 2) where is a 17.5 MW geothermal power plant. In the field of Kızıldere, the Paleozoic basement rocks are overlain by Pliocene sedimentary rocks which consist of Kızılkaya formation, Sazak formation, Kolonkaya formation, and Tosunlar Formation [12] an have good permeability. The Sazak formation composed of altered limestone forms the first shallow reservoir. The Paleozoic Igdecik formaton which consists of quartzite, marble, mica shists is of second deep thermal water reservoir.

The thermal field of Salavatlı with two (2) production wells to a depth down to 1510 m is located in the north of middle part of the rift zone of the Büyük Menderes (Figs. 1 and 2) and consists of Paleozoic metamorphic rocks and Miocene to Pliocene sedimentary rocks [13]. Paleozoic marble, quartzite, and mica shists form the thermal water reservoir in the field of Salavatlı.

The thermal field of Germencik with nine (9) production wells to a depth down to 2398 m is one of the geothermal areas with high enthalpy located in the north of the western part of the rift zone of the Büyük Menderes and consists of Paleozoic metamorphic rocks and Miocene to Pliocene conglomerates [14]. In the area, the conglomerates form the shallow reservoir whereas marble, quartzite, and mica shists are deep reservoir rocks.

Hydrogeology and hydrogeochemistry

At the surface, the metamorphic and sedimentary rocks in the thermal fields of Kızıldere, Salavatlı, and Germencik are intensively altered recognized by a distinct color change of the rocks and studies of rock microscopy on various thin sections and x-ray diffractometry analyzes. The hydrothermal alteration is distinguished by phyllic, argillic, and silicic ± haematitization zones. The phyllic and argillic alteration zones occur in the Paleozic metamorphic rocks whereas silicic ± haematitization alteration zones are an overprinting type and observed in Paleozoic metamorphic and sedimentary rocks. In addition, a new alteration type of carbonatization is recognized in sedimentary rocks which can be observed in the thermal fields of Kızıldere especially [5].

Due to high temperature, pressure, and CO_2 content in the thermal water reservoir of the study area, high temperature acid water infiltrates the soil formations and dissolves $CaCO_3$. The solution aims to get in an equilibrium constantly, but does not reach the suitable parameters of the corresponding environment. Thus, the solution loses the temperature, pressure, and CO_2 on its way to the surface, for which reason the pH values increase up to 9.2. Consequently, the geothermal fluid is unable to keep $CaCO_3$ in solution, but it precipitates and occurs in sedimentary rocks near the surface. The Silicic alteration zone can be observed in both Paleozoic metamorphic and Miocene to Pliocene sedimentary rocks [2].

During the present study the outflow of 14 thermal springs and 14 production wells has been sampled in different seasons since 1992. Additionally, 240 rock samples were collected. The thermal waters flow out of clastic sediments of Miocene to Pliocene age. The discharge of thermal waters is linked to faults which strike in E-W direction dip vertically. The surface temperatures of the thermal waters are 99 °C in Kızıldere, 45 to 95 °C in Salavatlı, and 30 to 92 °C in Germencik whereas the geochemical thermometers show reservoir temperatures of 200 to 240 °C in Kızıldere, 162 to 180 °C in Salavatlı, and 216 to 232 °C in Germencik. The total dissolved solids of the thermal waters ranges from 1800 to 6000 mg/l. At the surface the scale formations are generated by decreasing temperature and pressure. The scale formations consist of carbonates with high Sr anomalies and minor contents of silicates and sulfides. These minerals are mostly aragonite and calcite with high Au and Sb contents.

Hydrogeochemically, the thermal waters can be considered as Na-(Cl)-(SO_4)-HCO_3 type (Fig. 3) and are distinguished by an increase and a decrease of dominantly cations, anions, and trace elements from marine towards continental environment. Trace elements which indicate intensive high-temperature water-rock interaction such as $B^{(III)}$ and F^-, are found in high concentrations in these waters. With exception of As, Sb, and Hg, the thermal waters in the investigated fields are very poor in heavy metals. As, Sb, and Hg are known to precipitate mostly at the surface.

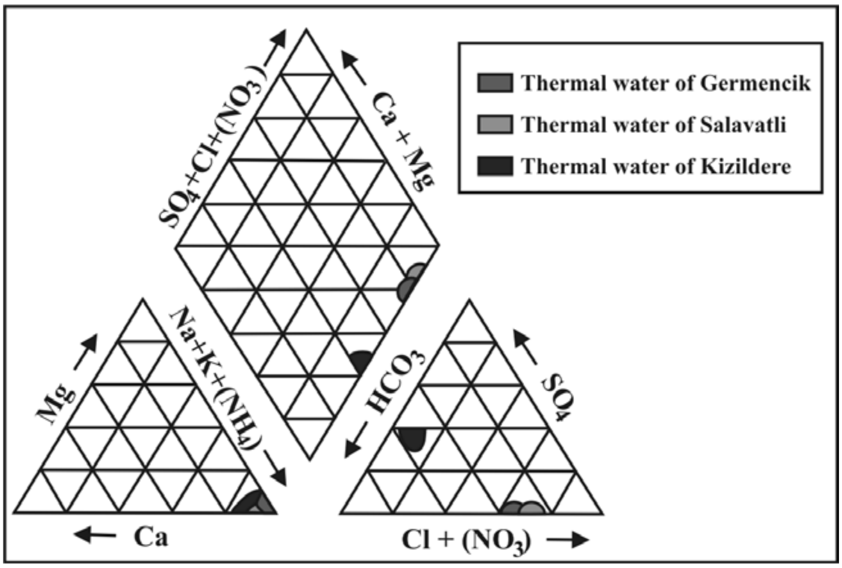

Fig. 3: Thermal waters of the thermal fields of Kızıldere, Salavatlı, and Germencik in the rift zone of the Büyük Menderes. See for data [4].

There is a close correlation between F and B in depending of the increasing Na contents and the decreasing Ca contents in high temperature waters [2, 15, 16]. The origin of $B^{(III)}$ can be attributed to mineral phases, i.e. tourmaline, biotite in metamorphic rocks, and boron deposits at depth. Fluorine can be lead either to a volcanic activity or to the lower Ca contents in the fluids.

Isotope geochemistry

Samples from hot springs, production wells, and groundwaters in the rift zone of the Büyük Menderes have been analyzed for their oxygen-18, deuterium and tritium contents. Additionally, the thermal waters of Kızıldere were considered due to contents of ^{13}C and ^{14}C. The stable isotope contents of δ^2H and $\delta^{18}O$ are represented in Fig. 4. The above mentioned rainwaters and mixed groundwater-thermal water systems lie along the meteoric water line whereas the high temperature deep groundwater systems deviate from the MWL suggesting a fluid-rock interaction under high temperature conditions. The differences in the degree of isotope shift from Kızıldere to Germencik indicate a mixing between three thermal waters which are characterized by δ^2H, $\delta^{18}O$, $\delta^{13}C$, ^3H, and ^{14}C values.

The tritium measurements reveal that (i) the thermal waters of Kızıldere, Salavatlı, and Germencik do not contain any measurable tritium and (ii) the mineralized groundwater and groundwater-thermal water systems contain atmospheric and anthropogenic tritium. Therefore, the tritium is not suitable for the age determination of the thermal waters of Kızıldere, Salavatlı, and Germencik. According to ^{13}C data, the origin of CO_2 might be attributed to magmatic activity as well as to reaction of thermal waters with carbonate rocks at depth [4]. These thermal waters show ^{14}C contents under detection limit because of the dilution of ^{14}C by high contents of CO_2 (Fig. 5) . Under the consideration of this fact, the thermal waters of Kızıldere, Salavatlı, and Germencik might be interpreted as old waters with a relatively age of 10.000 to 30.000 a.

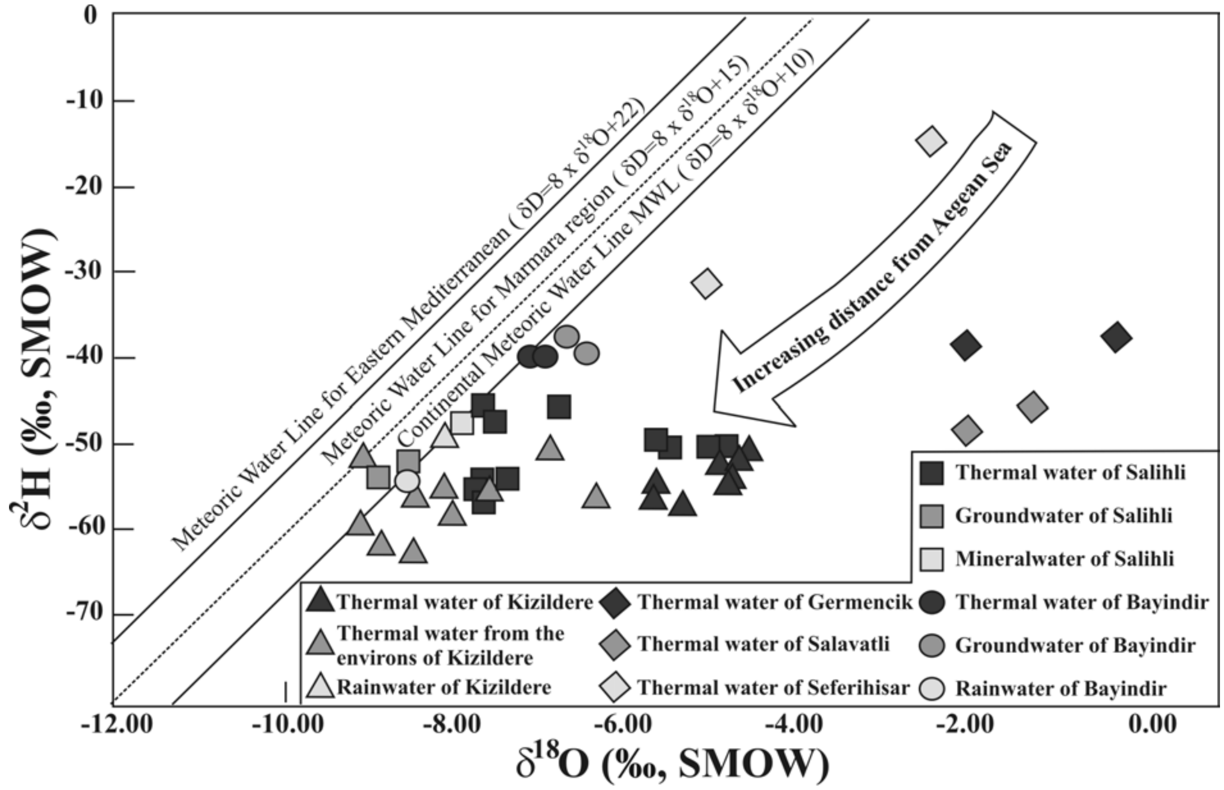

Fig. 4: Plot of δ^2H versus $\delta^{18}O$ of thermal waters of Kızıldere, Salavatlı, and Germencik in the rift zone of the Büyük Menderes. For comparison, stable isotope values from other localities were recorded. See for data [4].

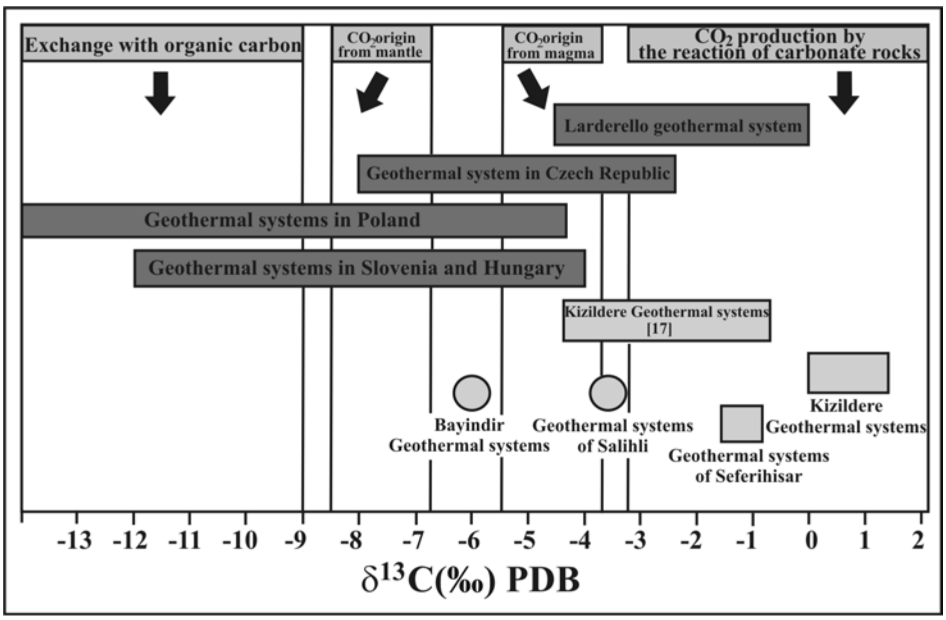

Fig. 5: $\delta^{13}C$ values in thermal waters of Kızıldere in the rift zone of the Büyük Menderes. For comparison, $\delta^{13}C$ values from other localities were recorded. See for data [4].

Discussion and conclusions

The investigated thermal waters of Kızıldere, Salavatlı, and Germencik are of meteoric origin. The meteoric waters in the drainage area percolate at fault zones and permeable clastic sediments into the reaction zone of the roof area of a magma chamber situated at a probable depth of up to 4 km where meteoric fluids are heated by the cooling magmatic melt and ascend to the surface due to their lower density caused by convection cells. The heating of the thermal waters by a subvolcanic activity are proven by the distinctly enrichment of mantle helium in geothermal fluids of Kızıldere [18, 19] which might be interpreted as ^{3}He surplus in comparison to pure continental crustal fluids. This high value of mantle helium might be interpreted that basic volcanic rocks from the earth mantle show an interaction with the geothermal fluids in the environs of the thermal field of Kızıldere. Besides some intrusive rocks in the rift zones of Menderes Massif, calkalcaline basic to intermediate volcanic rocks exist which are generated from Middle Miocene to recent. For example, the basalts of Kula 150 km northern part of the investigated area, occur in a young age of 18.000 a. Thereby, the presence of magma chamber at depth of the rift zone of Büyük Menderes is not to exclude and must be taken into consideration, i.e. volcanic activities in Denizli and Söke.

Additionally, it is noticeable that the geothermal gradients form second possibility to heat the meteoric waters in the area, which correspond to the intensity of heat flow and earthquake activity. Nevertheless, the waters at depth react with heated rocks which leads to water-rock interaction. The volatile components of CO_2, SO_2, HCl, H_2S, HB, HF, and He out of the magma reach the thermal water reservoir where an equilibrium between altered rocks, gas components, and fluids performs. Thus, the thermal waters ascend in the tectonic zones of weakness at the rift zone of the Büyük Menderes in terms of hot springs, gases, and steams.

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