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Hydrogeological, Hydrogeochemical and Isotope Geochemical Modeling of the Thermal Waters in the Continental Rift Zones of the Menderes Massif, Western Anatolia, Turkey

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ABSTRACT

The tectonic position of the eastern Mediterranean area between the Eurasian and African plates is controlled by the Anatolian and Aegean micro plates. The plate tectonic development results in the uplift of the Menderes Massif showing a dome shaped structure due to compressional tectonic features from Oligocene to Middle Miocene. From Early to Middle Miocene, the continental rift zones of the Büyük Menderes, the Küçük Menderes and the Gediz were formed by extensional tectonic features, which strike E-W generally and are represented by a great number of thermal waters, epithermal Hg, Sb, and Au mineralizations, and volcanic rocks of Middle Miocene to recent age. The thermal waters and epithermal mineralizations are related to faults, which strike preferentially NW-SE and NE-SW and are located diagonally to the general strike of the rift zones. These faults are probably generated by compressional tectonic stress, which leads to the deformation of uplift between two extensional rift zones.

The thermal waters of Kızıldere, Bayındır, and Salihli represent typical examples of active geothermal waters in the investigated area. 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 in a probable depth of up to 5 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 volatile components of CO_2, SO_2, HCl, H_2S, HB, HF, and He that are released out of the magma reach the geothermal water reservoir where equilibrium between altered rocks, gas components, and fluids occurs. Finally, the geothermal waters ascend along tectonic zones of weakness at the continental rift zones of the Menderes Massif, forming hot springs, gases, and steams. These fluids are characterized by high to medium CO_2, H_2S and NaCl contents.

1. INTRODUCTION

Between the Eurasian and African plates, the tectonic position of the eastern Mediterranean area is controlled by the situation of the Anatolian and Aegean micro plates. This plate-tectonic development results in the lifting of the Menderes Massif due to compressional tectonic features of the Middle Miocene. From the Tortonian to Pleistocene, the continental rift zones in the Menderes Massif were formed because of extensional tectonic features. In these continental rift zones, thermal waters and epithermal deposits are related to faults that strike preferentially NW-SE and NE-SW and are diagonal to the general strike of the rift zones. These faults are probably generated by the compressional tectonic stress, which leads to deformation of the uplifted area between two extensional rift zones. In addition to earthquake activity and heat flow anomalies in the continental rift zones of the Menderes Massif, the important localities of calc-alkalic basic towards acidic volcanic rocks were mapped. They are distinguished by an Rb/Sr age of 15,0 ± 0,2 Ma in Karaburç, an K/Ar age of 16,7 ± 0,5 Ma in Yenişehir (Özgür et al.,1997; Özgür, 1998) and an 7,5 Ma age of 20.000a in Kula (Ercan et al., 1992) and can be classified into Middle Miocene. These volcanic rocks are considered to be products of continental crust due to isotope analyses of $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ and are considered as the heat source for the thermal waters in the rift zones of the Menderes Massif (Özgür, 1998).

We have selected three geothermal fields of Kızıldere, Bayındır and Kurşunlu which are located in the rift zones of the Büyük Menderes, the Küçük Menderes and the Gediz and were investigated circumstantially (Fig. 1). The aim of this paper is to present the hydrogeochemical and isotope geochemical features of the thermal waters in the rift zones of the Menderes Massif in combination with the origin and evolution of these waters and to make a hydrogeological model of the geothermal waters.

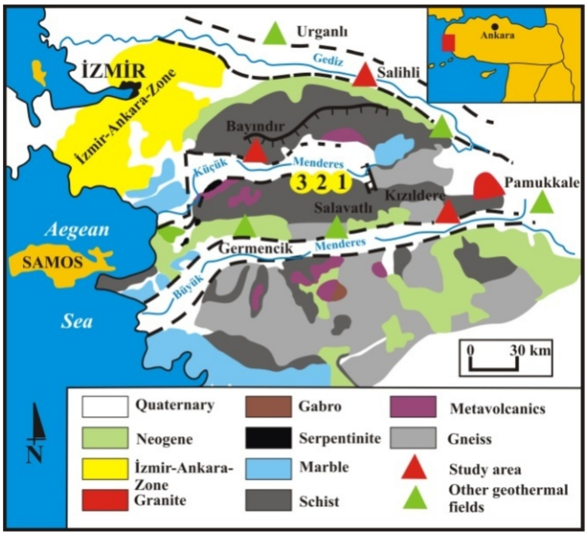

Fig 1. Geotectonic development of the Menderes Massif and continental rift zones. 1: Hg deposit of Halıköy, 2: Sb deposit of Emirli, 3: Au deposit of Küre

2. GEOLOGICAL SETTING

The investigated thermal fields of Kızıldere, Bayındır and Kurşunlu are located in the rift zones of the Büyük Menderes, the Küçük Menderes and the Gediz within the Menderes Massif (Fig. 1). This massif is one of the oldest basements in Turkey and consists of (i) gneiss-core surrounded by a schist and marble envelope and (ii) an intensely deformed volcano-sedimentary sequence with incipient HP/LT metamorphism.

The rift zones with thermal waters are the result of extension, which is believed to be closely related to the northward movement of the Arabian plate in the east pushing Anatolia westwards through the North Anatolian and East Anatolian Faults. The southerly bending of the North Anatolian Fault in the northern Aegean and Greece prevents the escape of the Anatolian plate further westwards, thus placing the system in a locking geometry (Dewey and Şengör, 1979). This creates an E-W compression in the Menderes Massif which is relieved by N-S extension. The driving force of extension in the Aegean is believed to be subduction along the Hellenic Trench (McKenzie, 1978). For the timing of initiation of extension, an age within a range from 26 Ma (Spakman, 1989) to about 12 Ma (le Pichon and Angelier, 1979) to 5 Ma (Patton, 1992) is given.

The thermal field of Kızıldere and environs consists of Paleozoic metamorphic rocks and Tertiary to Quaternary sediments (Özgür, 1998). The metamorphic rocks are composed of gneisses, mica schists and the İğdecik formation, which is composed of mica schists, quartzites and marbles. The gneisses are located in the NW part of the investigated area and show an immediate change with high-grade metamorphic mica schists. The tourmaline content in the gneisses is remarkable, and together with the biotites plays an important role for high boron contents in thermal waters. The mica schists overlie the gneisses and are considered to be a garnet-muscovite-biotite-schist assemblage. The Iğdecik formation, which forms the last upper sequence in the thermal field of Kızıldere, consists of alternating beds of mica schists, quartzites and marbles and shows light metamorphic features. It is traversed by ruptures and fissures and forms the second reservoir with a temperature of 216 °C (Şimşek, 1985). The Pliocene sediments are of continental lacustrine origin and overlie metamorphic basement. The sedimentation began in the Late Miocene and continues up to today. These sediments can be divided stratigraphically as follows:

(1) The Kızılburun formation consists of basic conglomerates, which are made up of well-rounded gravels of metamorphic origin, clay stones, finely graded sandstones and marls. This formation has a total thickness of 400 m and forms in the field as a morphological monad lock due to a high degree of consolidation. Because of its clay contents, the Kızılburun formation forms the ceiling of an aquiferous layer.

(2) The Sazak formation stands in particular contrast to other sediment formations due to its distinctly high carbonate contents. It consists predominantly of limestones, which are more clayey and sandy depending upon the facies. Moreover, a small amount of marls and sandstones are also present. The limestones in the Sazak formation are ostracod-, gastropod- and lamellibranch-bearing. The total thickness of the Sazak formation varies between 150 and 400 m. Tectonically, this formation is the hardest in the geothermal field due to hydrothermal silicification and reacts brittily, forming the outermost joints. This is a reason for the accumulation of block debris in valleys in which the tectonic and physical erosion is faster than the chemical. The Sazak formation is strongly fractured, porous to pitted, and is thereby an excellent aquifer. Therefore, it forms the first reservoir in the field of Kızıldere with a temperature of 200 °C. Due to its particular features, the Sazak formation has been located as a thermal water reservoir in the center of the continental rift zone of the Büyük Menderes, at a depth of 800 m by gravimetric and geoelectric methods (Guidi et al., 1990).

(3) The Kolonkaya formation is an alternation of sandstones, clay stones and clayey limestones. This formation has a thickness of 500 m and is gastropod- and lamellibranch-bearing. It is distinguished by a local hydrothermal alteration of silicification ± hematization at the outlets of thermal waters and steams.

(4) As the youngest Pliocene to Plio-Quaternary sediment formation, the Tosunlar formation in the thermal field of Kızıldere, shows an insignificant degree of consolidation, scarcely differs from the Kolonkaya formation and forms an alternation of sandstones, gravel stones, fine-graded sandy and clayey marls and limestones. It changes into Quaternary alluvium and is partly cultivated. This formation has a thickness of 500 m.

(5) In Middle Miocene, the continental rift zone of the Büyük Menderes formed with a general strike in the E-W direction. Tectonically, the thermal waters in Kızıldere and environs are associated with the faults in NW-SE or NE-SW directions, which are located diagonal to the general strike. These subsequent faults can be generated by a compression situation, which led to the deformation of two horst areas lying between two extension rifts. The rift zone of the Büyük Menderes is associated with thermal waters in Kızıldere and other localities and volcanic rocks in Denizli, Söke und Selçuk. The volcanic rocks in Denizli show an Upper Pliocene age. The volcanic rocks of Kula in the rift zone of the Gediz have an age varying from 7,5 Ma to 20.000a (Ercan et al., 1992).

The thermal field of Bayındır is located in the northern part of the rift zone of the Küçük Menderes, in the southwestern part of a Permocarboniferous unit consisting of alternating phyllite, muscovite-quartz-schist and marble, which stretches from Bayındır to Salihli, is overthrusted on the autochthonous schists of the Menderes Massif, and is considered to be part of the Bayındır formation when compared with marbles that form the basement in the thermal field of Bayındır. Stratigraphically, the quartzites form the oldest rocks und are distinguished by an well-developed fracture system, which is very important for the formation of thermal waters. The thickness of this rock sequence varies between 50 and 100 m. The rock is composed of 60 to 70 percent quartz, 23 to 35 percent muscovite and 5 percent opaque minerals. As accessory components, it contains feldspar, tourmaline, chlorite, calcite, rutile and zircon. The opaque components are graphite, hematite, pyrite and iron hydroxide. The mica schists alternate with quartzites and marbles and display a fine to mm-sphere reaching schistosity. The mica schists are composed of 25-65 percent muscovite, 20-30 percent quartz and 15-20 percent of the secondary constituents zoisite, clinozoisite and tourmaline, with feldspar, biotite, hematite and zircon as accessory minerals. The mica schists are impermeable and play an important role for the formation of a thermal water reservoir in quartzites and marbles with a good fracture system; thereby, mica schists can be considered as impermeable cap rocks and basement. The marbles occur as alternating layers in mica schists and have thicknesses from 10 to 200 m. These rocks show a good developed fracture system which is of major importance for the formation of thermal waters. The marbles are composed of 50-85 percent calcite, 15-35 percent quartz and muscovite, and up to 10 percent of opaque components such as graphite, magnetite and limonite. As accessory minerals, chlorite, zoisite, zircon and pyrite occur in the rocks.

The thermal fields of Kurşunlu and Çamurlu, located at Salihli in the rift zone of the Gediz, are composed of Permocarboniferous metamorphic rocks, Miocene to Pliocene sedimentary rocks and Quaternary alluvium. The Precambrian to Cambrian gneisses are located in the southern part of the thermal field, form the basement in the study area and are overlain by mica schists. The mica schists are composed of alternating phyllites, quartzites and marbles. The quartzites and marbles have a well-developed fracture system and can therefore be considered as reservoir rocks. The impermeable mica schists play a role of cap rocks and basement. The mica schists are separated by a detachment fault from the Miocene and Pliocene sedimentary rocks (Hetzel, 1995).

3. HYDROGEOLOGICAL FEATURES

The groundwater conditions in the drainage area of thermal waters of Kızıldere can be reconstructed by morphological criterion and proof of analogy. The groundwater flows northwards at the northern side of the rift zone of the Büyük Menderes within the Buldan Horst, where the thermal waters are supplied immediately (Fig. 2). The distance from the watershed to the thermal waters is about 10 km. Consequently, the drainage area occupies an area from 100 to 150 square kilometers. With an annual precipitation of 430,15 mm and average annual temperature of 17,6 °C, the region of Kızıldere has semiarid climatic conditions. The greater part of precipitation takes place in the winter months from December to March, whereas aridity is predominant for the remainder of the time. The arid season leads to a deficit of groundwater; therefore, the surface waters play only a secondary role in the feeding of thermal waters. For thermal waters that are discharged by channels, a discharge rate of 8,1 to 8,5 x 10^6 m^3/a has been measured. The river of the Büyük Menderes is a watercourse that begins as a karst spring at Dinar near Isparta, flows past Sarayköy, Aydın and Söke and leads into the Aegean Sea at Akköy. The discharge rate of the river is 15-20 m^3/s in winter and 2 m^3/s in summer.

The thermal waters of Kızıldere show two different reservoirs, namely the first reservoir of the Sazak formation at depths of about 400 m and the second reservoir of the Igdecik formation at depths from 1000 to 1242 m. The second reservoir consists of Paleozoic schists, quartzites and marbles and forms the main reservoir for the exploitation of thermal waters in Kızıldere. Reservoir temperatures lie in the range of 148 to 198 °C in the Sazak formation and in the range of 200 to 212 °C in the İğdecik formation. According to Şimşek (1985), the gneisses occurring at greater depths form a third reservoir with temperatures from 250 to 260 °C.

A lowering of the pressure of thermal waters in the reservoir can occur due to extreme production; it clearly depends on the lack of a reinjection well. Moreover, there is evidence for the shift of points of steam outlets from higher areas to lower areas today. This shows a disappearance of the old points of steam outlets. It shows that a distinct lateral movement of the fields of steam outlets to the catchment area of the geothermal power plant has taken place. The lowering of the steam outlet level of about 100 to 150 m is due to a decrease of pressure of about 15 bar. The surface temperatures are 96-100 °C in Kızıldere, 62-88°C in Tekkehamam and Babacık, 37-55 °C in Pamukkale and Karahayıt and 40-54 °C in Yenice I and II. The Na/K-thermometer (Fournier, 1979) give reservoir temperatures of 220-248 °C in Kızıldere, 211-234 °C inTekkehamam and Babacık, 260-313 °C in Pamukkale and Karahayıt and 251-288 °C in Yenice I and II.

Groundwater flow in the drainage area of the thermal field in Bayındır is southwards on the northern part of the rift zone of the Küçük Menderes in Bozdag Horst, where the thermal water reservoir is supplied by meteoric groundwater; thereby, the Ilıca creek plays an important role (Fig. 3). The distance from the northern watershed is about 10 km. The drainage area occupies an area of 50 km^2. With an average annual precipitation of 652 mm and an average annual temperature of 17,4 °C, the region has semi-arid climatic conditions. A great part of precipitation occurs from December to March, during the rest of the year aridity is predominant. This arid period leads to a groundwater deficit; therefore, the deep holes in the rift zone of the Küçük Menderes are used for irrigation applications. In summer time, the agricultural irrigation leads to additional shortages of groundwater. The Küçük Menderes is the watercourse which springs at Bozdağ near Kiraz, flows by Ödemiş and Bayındır and leads into Aegean Sea near Selçuk.

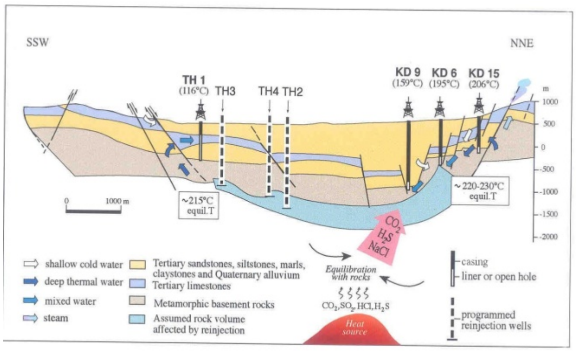

Fig 2. Simplified model of the thermal waters of Kızıldere in the rift zone of the Büyük Menderes within the Menderes Massif.

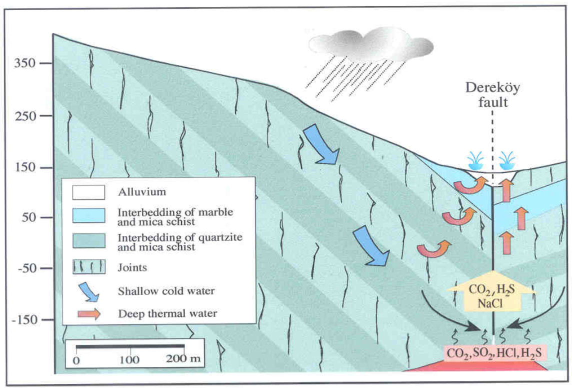

Fig 3. Simplified model of the thermal waters of Bayındır in the rift zone of the Küçük Menderes within the Menderes Massif.

In Salihli, groundwater flow in the drainage area of the thermal fields of Kurşunlu and Çamurlu is northwards on southern part of the rift zone of the Gediz; thereby, the thermal water reservoir is supplied by groundwater of dominantly meteoric origin (Fig. 4). The distance from the watershed in Bozdağ Horst to thermal fields of Kurşunlu and Çamurlu is about 10 km. The drainage area of the thermal fields occupies a total area of about 150 km^2. With an average annual precipitation of 652 mm and an average annual temperature of 16,6 °C, the drainage area of both thermal fields has semi-arid climatic conditions. The Gediz is a watercourse which springs in the northern part of Kula, is supplied by a system of tributaries and leads into the Aegean Sea in the northern part of İzmir. The discharge rate of the Gediz is at 20-25 m^3/s in winter and 3-5 m^3/s in summer.

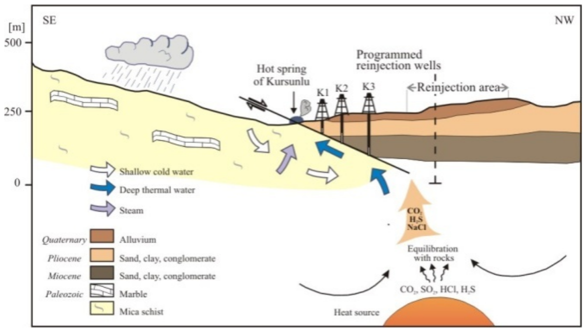

Fig 4. Simplified model of the thermal waters of Salihli in the rift zone of the Gediz within the Menderes Massif.

4. HYDROGEOCHEMICAL FEATURES

During the present study, the outflow of 20 thermal springs, 12 drill holes and 16 groundwater springs were sampled in different seasons from 1992 up to now. Additionally, we have collected about two hundred rock samples (Özgür, 1998).

Generally, the thermal waters of Kızıldere, Bayındır and Salihli can be classified as Na-(SO_4)-HCO_3 type (Fig. 5). In the drainage area of Kızıldere, the thermal waters of Kızıldere, Tekkehamam and Babacık can be classified as Na-(SO_4)-HCO_3 type, whereas the thermal waters of Pamukkale and Karahayıt show Ca-Mg-HCO_3 type exchange waters (Özgür, 1998). The origin of Na^+ in the thermal waters is linked to metamorphic rocks in the substratum, while carbonate rocks in the reservoir form the origin for Ca^{2+} and Mg^{2+}.

The high-temperature thermal waters of Kızıldere demonstrate TDS values from 5000 to 5500 mg/l and high mineralization rates (Özgür, 1998). Before the separator, the pH values of these waters range from 6 to 7, which correspond with the pH values of natural thermal springs in the environs. The HS^- ions in Babacık show values up to 5 mg/l. In comparison, the thermal waters of Kızıldere show HS- values below 0,02 mg/l. For the sulfur system in this aquatic environment, the following reactions are demonstrated:

$$H_2S + 4H_2O \Rightarrow H_2SO_4 + 4H_2$$

$$SO_2 + 4H_2O \Rightarrow 3H_2SO_4 + H_2S$$

Thus, magmatic sulfur provides a source for H_2S, H_2 and SO_4^{2-} (Hattori and Cameron, 1986). The entry of sulfur compounds can be assimilated and transported to the surface, which could be observed in reinjection wells in Tekkehamam at 2000 m depth and in Kızıldere 2261 m depth:

$$FeS_2 + 2H_2O \Rightarrow FeOOH^+ + H_2S + HS^-$$

HS^- or H_2S ions in thermal waters, which are either of magmatic origin or can be dissolved from sulfides by weathering, can be oxidized, ascend to the surface and release sulfur:

$$2H_2S + O_2 \Rightarrow 2H_2O + 2S$$

In the carbonate-bearing sedimentites, which are directly associated with thermal springs, gypsum efflorescences could be observed. The formation of gypsum stands in contrast to carbonatization.

$$2CaCO_3 + HCO_3^- + 2H + HS^- + H_2S + 4O_2 \Rightarrow 2\,CaSO_4 + 3H_2O + 3CO_2$$

This indicates that the sulfur system carries the principal responsibility; thereby, the existence of water is assumed.

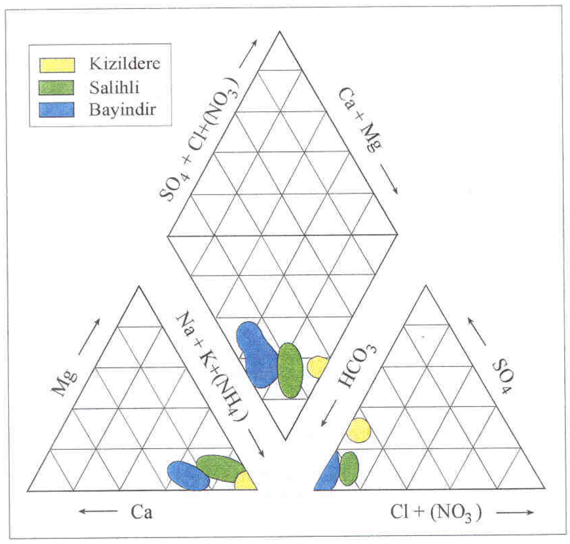

Fig 5. Geothermal waters of the thermal fields of Kızıldere, Bayındır and Salihli within the Menderes Massif.

In connection with nitrogen species, the following formula is valid.

$$3H_2 + N_2 \Rightarrow 2NH_3$$

The existence of traces of CO and COS can be explained as follows:

$$CO_2 + H_2S \Rightarrow COS + H_2O$$

$$CO_2 + H_2 \Rightarrow CO + H_2O$$

Hydrogeochemically, the thermal waters of Kızıldere and environs are distinguished by (i) an enrichment of F^-, Si^{4+} and B^{3+}, (ii) an enhancement of trace metals such as As^{3+} and Sb^{3+} and (iii) a depletion of base metals in combination with Fe^{2+} and Mn^{2+} (Özgür, 1998). B^{3+} occurs in the thermal waters with values up to 30 mg/l. The origin of enriched B^{3+}can be linked to the solubility product by fluid-rock interaction in the reservoir; thus, magmatic origin can not be ruled out completely.

According to tendency, the volatile components of CO_2, HS^- and NH_3 indicate a magmatic input; this could be conditionally confirmed by isotope analyses of $^{11}B/^{10}B$. In connection with fluid-rock interaction, boron contents in thermal waters can be leached from mineral phases such as tourmaline and biotite in metamorphic rocks and boron minerals in sedimentary rocks. The experimental leaching tests of different rocks from Kızıldere show that gneisss and mica schists play an important role as a boron source. The thermal waters in Kızıldere and environs represent fluorine contents up to 35 mg/l. On the one hand, these high contents can indicate a magmatic origin of volatile components; on the other hand, the increasing value of fluorine in thermal waters depends upon Ca^{2+} contents, because there must be a corresponding Ca^{2+} donor in the environment in order to precipitate a corresponding amount of F^-. Otherwise, fluorine ions remain released, and the fluid is enriched with F^-. Depending upon temperature, fluorine and boron show a close correlation in thermal waters of Kızıldere and environs (Özgür, 1995). Accordingly, fluorine and boron show an approximate positive correlation that is probably based on (i) interconnection of thermodynamic control processes, (ii) applicability of boron as a tracer and (iii) substitution of both elements in boron-bearing minerals.

The thermal waters of Kızıldere represent average Si^{4+} contents of 115 mg/l, which have likely been leached from the silicates in the reservoir at a temperature of about 200 °C by fluid-rock interactions. Solubility equilibrium of Si depends upon the modification of amorphous silica, which allows high Si concentrations. When the thermal waters are separated as steam and fluid phase, this gives rise to a 25 percent water loss in terms of water steam, a CO_2 leakage and an Si enrichment in the fluid of 150 mg/l. Thus, the CO_2 leakage causes a pH increase to 9 at a temperature of 100 °C. At a temperature of 45 °C, the thermal waters in drainage basins represent average Si contents of 150 mg/l and a pH value of 9. The thermal waste waters of the geothermal power plant of Kızıldere should be reinjected in order to supply the thermal water reservoir constantly and remove agricultural danger for citrus fruits in the rift zone of the Büyük Menderes in view of environmental aspects. The precipitation of Si as precipitates represents a potential danger for the reinjection system as documented by thermodynamic and kinetic results (Giese, 1997). Thereby, Si precipitates will occur in the reinjection well depending on time, with regard to ion strength of pH values and temperature (below 100 °C).

The thermal waters in Kızıldere represent As values up to 1,08 mg/l and Sb values up to 0,21 mg/l (Özgür, 1998). Depending upon temperature, these elements show a close correlation in thermal waters. This is the case in the rocks as well. The rocks of the thermal field of Kızıldere have Au contents up to 6 ppb and Sb contents ranging from 194 ppb to 1373 ppb. The cap rocks, which are closely connected with thermal water reservoirs, represent high Ag contents of 1,21 ppm. These high Ag contents in the metamorphic rocks are represented by a high background value of 0,5 ppm. It shows that the metamorphic rocks were a former source for Au and Ag. The carbonate and silicate precipitates show Au contents up to 3,5 ppm and Ag contents up to 194 ppb. The base metals in the thermal waters show distinctive low contents, as expected.

The thermal waters of Bayındır are distinguished by a temperature of 46 °C, a pH value of 6,9, an Eh value of -94 mV, an average EC value of 1015 µS/cm and an average TDS value of 1399 mg/l (Özgür, 1998, 2001, 2003). They differ from the surface waters and groundwaters in respect to hydrogeochemical composition and standardization distinctly. In comparison to Kızıldere, the thermal waters of Bayındır show relatively poor fluid-rock interaction in low-temperature spheres, this is how a light paragenesis of alteration minerals was generated.

In the thermal fields of Salihli, there are five thermal springs of Kurşunlu and Çamurlu and three production wells (Özgür, 1998). Four of the thermal springs are located in Kurşunlu with temperatures from 96 to 36°C. One of them is situated in Çamurlu. The first well (K-1) located near the thermal spring has a depth of 42,5 m, a surface temperature of 96 °C, a surface pressure of 5,5 to 6,0 bar and a flow rate of 20 l/s. The second well (K-2) is located in the northern part of the first well and has a depth of 70 m, a surface temperatures of 96 °C and a flow rate of 45 l/s. The first 20 m depth consists of alluvium, the depth between 20,00 and 68,80 m is alternating mica schist and marble, and the depth between 68,80 and 70,00 m consists of marble. The third well is located in the northern part of the thermal field of Kurşunlu and shows a depth of 117 m, a surface temperature of 96 °C, a surface pressure of 5,5 to 6,0 bar and a flow rate of 80 l/s. Drill log of this third well shows Quaternary alluvium between 0 and 5 m, Pliocene sedimentary rocks from 5 to 83 m, Miocene conglomerates at depths from 83 to 92 m, Paleozoic marble from 92 to 104 m and Paleozoic alternation of mica schist and marble at depths from 104 to 117 m.

In the thermal field of Salihli, the thermal waters differ from groundwaters and surface waters hydrogeochemically (Fig. 2). The thermal waters of Salihli are of Na-K-HCO_3 type, and exchange water with groundwaters that show Ca-HCO_3 type. In comparison to Kızıldere, the low contents of F^-, SO_4^{2-}, As^{3+} and Sb^{3+} and the high contents Mg^{2+} and Ca^{2+} in the thermal waters of Salihli are distinctly conspicuous. The low contents of F^- can be correlated with increasing Ca^{2+}, because both elements in fluids can be precipitated as CaF_2. The ^3H isotopes in thermal waters of Salihli show the existence of water mixing; therefore, the components of anions and cations are diluted in comparison to Kızıldere and occur in present concentrations.

The geochemical thermometer shows reservoir temperatures of 147-170 °C (quartz), 140-160 °C (quartz with steam loss), 120-145 °C (chalcedony), 205-220 °C (Na-K), 195-215 °C (Na-K-Ca), 35-135 °C (Na-K-Ca-Mg), 240-260 °C (Na-Li), 120-155 °C (Mg-Li) and 100-120 °C (K-Mg). Of these, the thermometers of Na-K, Na-K-Ca and quartz correspond with Özgür (1998) and are more suitable.

5. ISOTOPIC SIGNATURES

The thermal waters of Kızıldere, Bayındır and Salihli can be classified as meteoric water due to the isotope ratio of $\delta^{18}O$ and δ^2H (Fig. 6). The ^3H contents in investigated thermal waters are attributed to atmospheric and anthropogenic effects. They indicate that the thermal waters of Bayındır and Salihli can be considered as mixing water. The thermal waters of Kızıldere show scarcely any mixing of young groundwaters, because ^3H contents are below the detection limit. The ratios of $\delta^{13}C$ in groundwaters, mixing waters and thermal waters reveal that the origin of CO_2 can be linked to magmatic activity by subvolcanism in basement rocks and to reactions with carbonate rocks. The δ^3He surplus in thermal waters of Kızıldere reveal interactions of these fluids with basic to intermediate volcanic rocks of mantle origin that are still cooling and the existence of a subvolcanic intrusion. CO_2 production in connection with carbonate rocks in the reservoir dilutes ^{14}C in thermal waters, by which the age determination with ^{14}C is almost impossible.

6. DISCUSSION: HYDROGEOLOGICAL MODELLING OF THE THERMAL WATERS

In active thermal fields of Kızıldere, Bayındır and Salihli, groundwater flow takes place in drainage areas from higher spheres around the watershed in horsts to lower spheres located rift zones where the groundwaters ultimately find the watercourse (Fig. 7).

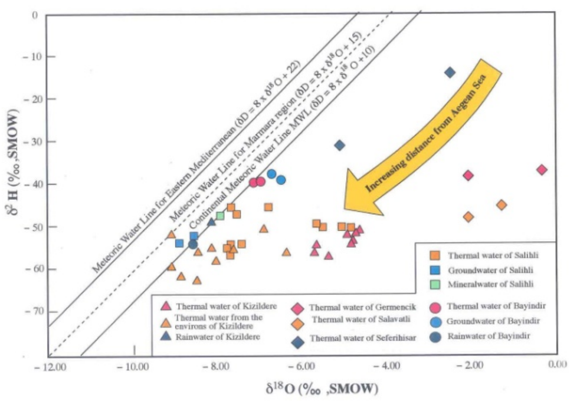

Fig. 6. Plot of δ^2H versus δ^{18}O of thermal waters of Kızıldere, Bayındır and Salihli.

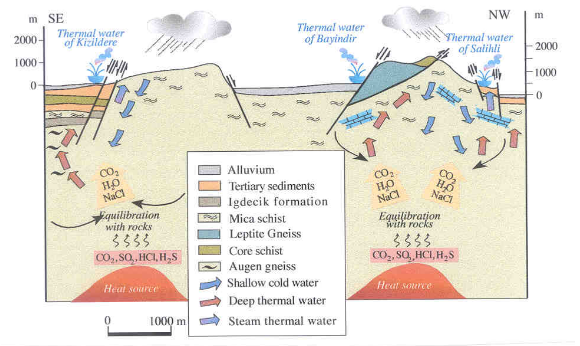

Fig. 7. Simplified presentation of geothermal model of the thermal waters in the rift zones of the Büyük Menderes, Küçük Menderes and Gediz within the Menderes Massif.

These meteoric waters in the drainage area percolate at fault zones and through permeable clastic sediments into the reaction zone of the roof area of a magma chamber situated at a probable depth of up to 5 km. Here, meteoric fluids are heated by the cooling magmatic melt and ascend to the surface due to their lower density, caused by convection cells. The volatile components of CO_2, SO_2, HCl, H_2S, HB, HF, and He out of the magma reach the geothermal water reservoir where an equilibrium between altered rocks, gas components, and fluids occurs. Thus, the geothermal waters ascend in the tectonic zones of weakness at the continental rift zones of the Menderes Massif in the form of hot springs, gases, and steams. These fluids are characterized by high to medium CO_2, H_2S and NaCl contents. It is very important that the fluids indicate a reduced pH-neutral environment after equilibrium adjustment with hard rocks in the reaction zone, namely in the roof area of magma chamber (Giggenbach, 1992). In superficial areas, i.e. beneath a depth of 550 m in Kızıldere with a pressure of 50 to 100 bar, a temperature of 200 to 220 °C and a pH value of lesser than 5,0, fluids come to boiling by decrease of pressure; thereby, CO_2 and H_2S rich steams are split off from thermal waters, which can lead to formation of sulfate-rich waters after condensation and surface oxidation. The thermal waters are consequently exploited for various uses, i.e. for geothermal energy, balneology, and green houses.

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