Hydrogeological Modelling of Geothermal Waters in Yenice (Buldan, Denizli) and Environs, Turkey

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Abstract. The study deals with hydrogeological modelling of geothermal waters in Yenice located in the southern margin of the continental rift zone of the Büyük Menderes where it incorporates with the rift zone of the Gediz within the Menderes Massif in which hydrogeological, hydrogeochemical and isotope geochemical methods were used. In Yenice and environs, Paleozoic metamorphic rocks forms the basement overlain by Neogene sedimentary rocks such as Kızılburun formation, Sazak formation, Kolonkaya formation and Tosunlar formation. These rocks are overlain by Quaternary alluviums and travertine deposits. Geothermal waters in the area of Yenice are of meteoric origin and show intense water-rock interaction. These geothermal waters can be considered as Ca-Na-(SO₄)-HCO₃ type. Moreover, geothermal waters have an order of cations of Na+K>Ca>Mg and anions of HCO₃>SO₄>Cl. Geothermal waters of the study area are distinguished by surface temperatures from 36 to 70 °C, pH values between 6 and 6.85 and electrical conductivity values ranging from 1950 to 5000 µS/cm. According to calculations of geochemical thermometers, geothermal waters of Yenice show reservoir temperatures between 170 and 230 °C and can be classified as immature waters.

1. Introduction
Geothermal waters of Yenice and environs are located in the northern margin of the rift zone of the Büyük Menderes in the east of the Menderes Massif where it incorporates with the continental rift zone of the Gediz within the Menderes Massif [Figure 1; 1]. The aim of this paper is to depict hydrogeological and hydrogeochemical and isotope geochemical characteristics of geothermal waters in Yenice and environs to clarify the origin of these waters. Moreover, it is desirable to represent an hydrogeological model for the formation of geothermal waters in the study area[2].

2. Material and methods
In the area, we have collected 7 samples in accompaniment of in-situ measurements of temperatures, pH values, Eh (mV) values, electrical conductivity values (µS/cm), dissolved oxygen values (mg/l) and alkalinity values (mmol/l) from 1998 to 2018. ICP-OES methods were used for analyses of cations[Table 1]. The analyses of anions have been realized by using IC methods. The software program AquaChem 3.7 was used for calculation of hydrogeochemical species and representation of graphical components [3].
3. Results

3.1 Geologic setting
In the area, Paleozoic metamorphic rocks consisting of quartzites and schists form the basement which can be considered as permeable as well as impermeable rocks due to formation of reservoir conditions. These rocks are overlain by Paleozoic Igdecik formation composed of marbles, quartzites and schists and can be classified as deep reservoir rocks[2]. Late Early to Early Middle Miocene Kızılburun formation, which is composed of conglomerates, sandstones, claystones, siltstones, mudstones, limestones and coals, underlie this rock sequence discordantly and form the cap rocks for the deep reservoir. This rock sequence is overlain by Early Late Miocene to Middle Miocene Sazak formation concordantly, which consists of sandstones, marls, clayey limestones and gypsum, and can be considered as shallow reservoir. Middle Late Miocene to Early Pleistocene Kolonkaya formation, which consists of claystone, siltstones, marls, clayey limestones, sandstones and conglomerates, overlies the last rock sequence concordantly and is of impermeable cap rock. The Kolonkaya formation is underly by Quaternary Tosunlar formation discordantly. The Tosunlar formation consists of conglomerates, sandstones and mudstones is overlain by Quaternary alluviums and travertine deposits.

![Geological sketch map of Yenice and environs in the northern part of the Rift zone of the Büyük Menderes within the Menderes Massif. 36: Geothermal waters of Yenice [modified from 1].](image-url)
Table 1. Hydrogeochemical analyses and in-situ measurements of geothermal waters in Yenice and environs.

| Sample | T (°C) | pH | Eh (mV) | EC (μS/cm) | Ca²⁺ (mg/l) | Mg²⁺ (mg/l) | Na⁺ (mg/l) | K⁺ (mg/l) | HCO₃⁻ (mg/l) | Cl⁻ (mg/l) | SO₄²⁻ (mg/l) | Si (mg/l) | Sr (mg/l) | U (mg/l) | F⁻ (mg/l) |
|--------|--------|----|---------|-------------|-------------|-------------|-------------|------------|-------------|------------|--------------|-----------|----------|--------|--------|
| Y-1    | 45.8   | 6.13 | 32     | 2110        | 226.4       | 34.78       | 250.2       | 36.31      | 949.3       | 45.17      | 418.02      | 11        | 1.94     | 0.41   | 2.20    |
| MV011  | 35     | 6.13 | 136    | 1950        | 470         | 95          | 38          | 136        | 549         | 19.4       | 686         | 5         | 6.10     | 0.13   | 1.54    |
| MV012  | 52     | 6    | 232    | 2340        | 480         | 122         | 111         | 232        | 589         | 32.5       | 1220        | 6         | 9.80     | 0.33   | 2.38    |
| MV014  | 40     | 6.15 | 261    | 2300        | 295         | 40.50       | 279         | 261        | 702         | 39.8       | 334         | 10        | 4.60     | 0.48   | 2.55    |
| MV015  | 54     | 6.59 | 173    | 3130        | 283         | 40.50       | 557         | 173        | 934         | 55.7       | 725         | 25        | 7.40     | 0.95   | 3.37    |
| MV016  | 51     | 6.11 | 121    | 4380        | 890.9       | 185.30      | 543         | 61         | 671         | 95.0       | 1665        | 20        | 14.44    | 1.80   | 2.27    |
|        | 70     | 6.85 | 50     | 5000        | 11.51       | 0.58        | 1176        | 120        | 958         | 106.0      | 1030        | 62.5      | 0.28     | 4.75   | 11.50   |
3.2 Hydrogeology
A great number of geothermal waters occur in the eastern part of the rift zone of the Büyük Menderes. The study area of Yenice is located in the northern margin of the rift zone of the Büyük Menderes. In the area, the Sazak formation with a thickness of 300 m forms the first shallow reservoir due to primary permeability and tectonic structures like faults and fractures[1]. Paleozoic Igdecik formation with a thickness of about 250 m is of deep reservoir due to secondary permeability caused by tectonical structures like faults, fractures and fissures. Kızılburun formation is cap rock for the geothermal deep reservoir within the Igdecik formation. In addition, Kolonkaya and Tosunlar formations form the cap rocks for the shallow reservoir within the Sazak formation.

3.3 Hydrogeochemistry
The geothermal waters in the area of Yenice are of Na-Ca-(SO₄)-HCO₃ type waters in Piper diagram [Figure 2]. In the diagram of Na+K-Ca-Mg [Figure 3], geothermal waters are distinguished by Na+K and Ca contents respectively. In the geothermal waters of Yenice, there are predominant cations of Na+K>Ca>Mg and predominant anions of HCO₃>SO₄>Cl respectively. In the plot of SO₄-Cl-HCO₃, the anions of SO₄ and HCO₃ are distinguished by high contents whereas the Cl contents are low [Figure 4]. In the diagram of Na1/1000-K1/100-√Mg, the geothermal waters from the study area are of immature waters in comparison to geothermal waters of Kızıldere [Figure 5; 4; 5].

![Figure 2. Geothermal waters of Yenice and environs in Piper Diagram. For comparison, geothermal waters from other relevant areas were demonstrated.](image1.png)

![Figure 3. Plot of Na+K-Ca-Mg of geothermal waters of Yenice and environs. For comparison, geothermal waters from other relevant areas were demonstrated.](image2.png)
Figure 4. Plot of SO4-Cl-HCO3 of geothermal waters of Yenice and environs. For comparison, geothermal waters from other relevant areas were demonstrated.

Figure 5. Plot of Na1/1000-K1/1000-√Mg of geothermal waters of Yenice and environs. For comparison, geothermal waters from other relevant areas were demonstrated.

3.4 Isotope geochemistry
Plot of δ18O versus δ2H of the study area in Yenice is shown in [Figure 6]. In geothermal waters of Yenice, δ2H values range from -54.9 to -55.0 ‰, whereas δ18O values lie between -7.68 and -8.17 ‰. The samples of geothermal waters of Yenice deviate from the global meteoric water line (GMWL) which point to intense water-rock interaction. 3H values up to <1.0 TU show that there are no mixing process between fresh groundwaters and geothermal waters in the area of Yenice.

4. Discussion
As a model, the geothermal waters of Yenice (1) and (2) can be constructed hydrogeologically in the study area [Figure 7]. The area is recharged by infiltration of meteoric waters and reflects a common recharge from the both Sazak and Igdecik formations in the Yenice horst in the N [1]. For that, the normal faults in N directions are main conduits for the flow of geothermal waters. In the area, there are NW-SE trending faults and fractures, along which the geothermal waters circulate. Along the NW-SE trending faults in the area, geothermal waters emerge as hot springs, steams and gases. At depth up to
5 km, the meteoric groundwaters are heated by cooling magmatic melt in the reaction zone of a magma chamber, rise through major faults to the surface in the area of Yenice.

Figure 6. Plot of $\delta^{18}$O vs. $\delta^2$H in geothermal waters of the continental rift zones of the Menderes Massif including the geothermal waters which were demonstrated as thermal waters from the environs of Kızıldere[4].

Figure 7. Geothermal model of geothermal waters of Yenice and environs [modified from 1].
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