Hydrogeological Model of Geothermal Waters in Gölemezli and Environs, Western Anatolia, Turkey

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Abstract Study area is situated in 2 km NW part of the world famous travertine deposits of Pamukkale located in the node point of the Büyük Menderes and Gediz rift zones. Geologically, there are two rocks units for reservoirs in the area: (1) the Neogene Sazak formation forms the shallow reservoir and (2) the Paleozoic Iğdecik and Ortaköy formation forms the deep reservoir and are composed of marble, quartzite and schist alternations. In the area, in-situ measurements of temperatures, pH, Eh (mV), electrical conductivity values (µS/cm), dissolved oxygen values (mg/l) and alkalinity values (mmol/l) were realized. At the same time, 15 samples of geothermal waters and groundwaters in the study area were collected for cation and anion analyses by ICP-OES and IC. The geothermal waters of Gölemezli are of Na-Ca-(SO₄)-HCO₃ type waters whereas the geothermal waters of Pamukkale are classified as Ca-Mg-HCO₃ type waters. In Gölemezli, there are predominant cations of Na⁺+K>Ca>Mg and predominant anions of SO₄²⁻-HCO₃>Cl respectively. The triangular diagram of Na₁/₁₀₀₀-K₁/₁₀₀-Ma indicates an immature water in Gölemezli and environs. Finally, geothermal waters of Gölemezli and environs were represented as a conceptual model due to hydrogeological, hydrogeochemical and isotope geochemical data in this study.

1. Introduction
Study area is situated in 2 km NW part of the world famous travertine deposits of Pamukkale in the province capital of Denizli located in the node point of the Büyük Menderes and Gediz rift zones within the Menderes Massif [Figure 1]. In the area, there are a great number of geothermal waters with low-to moderate temperatures such as Gölemezli, Yenice, Karahayıt and Pamukkale. The aim of this paper is (i) to describe hydrogeological, hydrogeochemical and isotope geochemical aspects in the area and (ii) to create a conceptual hydrogeological model.

2. Material and methods
In the field campaign in Gölemezli from 2010 to 2018, 14 samples of geothermal waters and groundwaters were sampled [2; 3; 4; 5; Figure 2; Table 1]. At the same time, in-situ measurements such as temperatures, pH, Eh, electrical conductivity and dissolved oxygen values have been carried out [Table 1]. Additionally, alkalinity measurements were realized in the field campaign for calculation of HCO₃⁻ and CO₃²⁻ values. The cations of Na⁺, K⁺, Ca²⁺, Mg²⁺, Si⁴⁺ and B³⁺ were analyzed by using ICP-OES methods. The analyses of anions of F⁻, SO₄²⁻, NO₃⁻ and Cl⁻ were realized by IC
methods [Table 1]. For evaluation and representation of data, we used geochemical software program: Aqua Chem 3.7 [6].

Figure 1. Geological sketch map of study area in the eastern part of the rift zone of the Büyük Menderes[1]. Rectangle is the study area.

Figure 2. Sample locations of geothermal waters in Gölemezli and environs [adapted from 2; 3, 4; 5].
Table 1. Hydrogeochemical analyses and in-situ measurements of geothermal waters in Gölemezli and environs.

| Sample | T (°C) | pH  | Eh (mV) | EC (μS/cm) | Ca²⁺ (mg/l) | Mg²⁺ (mg/l) | Na⁺ (mg/l) | K⁺ (mg/l) | Cl⁻ (mg/l) | HCO₃⁻ (mg/l) | SO₄²⁻ (mg/l) | F⁻ (mg/l) | Si⁴⁺ (mg/l) | B³⁺ (mg/l) | SO₄ (‰) | δ¹⁸O (‰) | δD (‰) |
|--------|--------|-----|---------|------------|-------------|-------------|------------|-----------|-----------|---------------|--------------|-----------|-----------|-----------|---------|---------|---------|
| G-1    | 58     | 6.56| -214    | 4179       | 421.2       | 118.3       | 505.7      | 56.9      | 1342      | 72.7          | 1570.9      | 3.32      | 49.1      | 14.57     |         |         |         |
| EU-1   | 34.8   | 6.61| 155     | 2420       | 442         | 94.1        | 42.5       | 5.52      | 1176.1    | 14.1          | 706         | 1.82      | 30.1      | 0.8       |         |         |         |
| EU-2   | 34.7   | 6.69| 157     | 2410       | 454         | 90.4        | 42.1       | 5.6       | 1125      | 14.8          | 681         | 1.40      | 30.5      | 0.9       |         |         |         |
| EU-3   | 34.1   | 6.91| 144.3   | 2410       | 445         | 96.1        | 42.4       | 5.45      | 1147.3    | 14.7          | 662         | 1.55      | 30.4      | 0.8       |         |         |         |
| EU-4   | 34.1   | 6.66| 128.7   | 2410       | 325         | 95.5        | 42.5       | 5.45      | 1164.2    | 12.9          | 661         | 1.34      | 30.5      | 0.8       |         |         |         |
| EU-5   | 44     | 6.67| 136.8   | 25-50      | 367         | 318         | 117        | 24.3      | 1109.3    | 38.8          | 915         | 1.85      | 29.7      | 1.6       |         |         |         |
| AB-1   | 35     | 6.22| 210     | 2410       | 455.05      | 69.9        | 48.45      | 15.55     | 1128.5    | 12.29         | 624.8       | 1.35      | 19.19     | 0.71      | -9.14   |         | 3.3      |
| AB-2   | 33     | 6.24| 229     | 2420       | 441.9       | 71.25       | 42.92      | 3.1       | 1159      | 12.64         | 611.9       | 1.39      | 19.12     | 0.46      | -9.23   |         |         |
| AB-3   | 52     | 6.39| 113     | 2780       | 528.5       | 123.15      | 131.65     | 21.8      | 1189.5    | 27.23         | 872.3       | 1.88      | 28.84     | 0.96      | -8.56   | -57.3    |         |
| AB-4   | 48     | 6.18| 151     | 2810       | 440.75      | 95.3        | 124.2      | 17.25     | 1128.5    | 51.91         | 879.7       | 2.21      | 21.32     | 1.6       |         |         |         |
| AB-5   | 23.9   | 8.01| 287     | 448        | 3.77        | 0.48        | 166.4      | 0.65      | 231.8     | 5.57          | 321.8       | 0.34      | 5.1       | 0.22      |         |         |         |
| AB-6   | 67     | 6.89| 194     | 2420       | 148.75      | 72          | 247.7      | 52.2      | 1159      | 81.41         | 377.7       | 0.99      | 29.92     | 3.4       |         |         |         |
| AB-7   | 60     | 6.69| 144     | 3470       | 555.5       | 84.25       | 207.85     | 42.95     | 207.4     | 27.44         | 451.9       | 1.20      | 24.31     | 2.99      |         |         |         |
| AB-8   | 59     | 6.28| 253     | 4460       | 464.15      | 106.5       | 451.6      | 45.05     | 1250.5    | 70.84         | 1664        | 2.24      | 59.03     | 5.74      | -8.32   |         |         |
3. Results

3.1. Geologic setting

In Gölemezli and surrounding area, Paleozoic rocks form impermeable basement which consists of diversely schists and quartzites [Figure 3]. Mesozoic limestones, Eocene to Pliocene sedimentary rocks Quaternary alluviums and travertine deposits in the area overlie the Paleozoic basement. The travertine deposits are linked with some parts of the Pamukkale fault. Additionally, the travertine deposits can also be observed somewhere else.

![Figure 3. Geological map of Gölemezli and environs [adapted from 2; 3; 4; 5].](image)
3.2. Hydrogeology
First of all, Paleozoic marbles and quartzites in the alternation of marbles, quartzites and schists located in the N and NE parts of Gölemezli are of first deep reservoir in the area. Mesozoic limestones located in N part of Gölemezli form the second shallow reservoir. Miocene to Pliocene sedimentary rocks and Quaternary alluviums occur in the study area which indicate a shallow reservoir in the area. Kolonkaya and the Tosunlar formations in Pliocene age show thickness up to 600 m and consist of claystones, marls and sandstones and. The last rock sequences can be considered as cap rocks for shallow reservoir.

3.3 Hydrogeochemistry
Geothermal waters in Gölemezli are of Na-Ca-SO₄-HCO₃ type waters in Piper diagram [Figure 4]. As shown in [Figure 5], geothermal waters of Gölemezli and environs are of predominant regarding the anions of SO₄ and HCO₃. 3 samples of geothermal waters are of predominant concerning Na+K, as shown in the triangular diagram of Na+K-Ca-Mg [Figure 6]. In comparison, the other 12 samples are predominant with respect to Ca contents. The investigated geothermal waters coincide with immature waters in general, as shown in the diagram of Na1/1000-K1/100-√Mg [Figure 7]. One (AB-5) sample of these waters corresponds with partially equilibrated waters.

![Figure 4](image_url). Plot of Geothermal waters of Gölemezli and environs in Piper diagram [modified from 2; 3; 4; 5].
Figure 5. Plot of $\text{SO}_4$-$\text{Cl}$-$\text{HCO}_3$ of geothermal waters in Gölemezli and environs [modified from 2; 3; 4; 5].

Figure 6. Plot of $\text{Na}^+\text{K}$-$\text{Ca}$-$\text{Mg}$ of geothermal waters in Gölemezli and environs [modified from 2; 3; 4; 5].
3.4. Isotope geochemistry

The plot of $\delta^{18}$O versus $\delta^2$H shows that geothermal waters in Gölemezli and environs originated from meteoric waters. According to [7], geothermal waters are far from the equilibrium and confirm mixing with cold groundwaters. Mixing process between geothermal waters and cold groundwaters takes place during the upward migration of geothermal waters.

**Figure 7.** Plot of Na/1000-K-100-$\sqrt{Mg}$ of Geothermal waters of Gölemezli[. modified from 2; 3; 4; 5].

**Figure 8.** Plot of $\delta^{18}$O versus $\delta^2$H of geothermal waters of Gölemezli and environs. For the data of stable isotopes see [2; 3; 5; 8].
4. Discussion
Geothermal waters in Gölemezli represent a conceptual model in which has been investigated comprehensively by [4; 8; Figure 9]. In a such process, cold groundwaters of meteoric origin in catchment area flow through tectonical structures like faults and fractures into reservoir rocks. In the reservoir, which consists of marbles, quartzites and limestones in the study area, geothermal waters may be heated by cooling magmatic melts of a possible magma chamber of a 5 km depth. For that, Middle Miocene to recent volcanics with an age of 18.000 a like Denizli and Kiraz volcanics as well as Kula volcanics are responsible. In this simple process, geothermal waters ascend to the surface due to their lower density. In the process, plate tectonical convection cells play an important role. At the same time, the volatiles achieve geothermal reservoir, where an equilibrium between all components such as rocks, gases, and geothermal waters take place. Finally, geothermal waters ascend along the tectonical structures like faults and fractures at the rift zones of the Büyük Menderes and Gediz in form of steams and hot springs.

Figure 9. Hydrogeological conceptual model of geothermal waters in Gölemezli [modified from 3; 4: 9; 10; 11].

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