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# Tectono-Thermal Modeling Of Geothermal Systems and Boron Isotope Ratios in Geothermal Waters of Western Anatolia

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## ABSTRACT

Development of NW-SE trending grabens at Neotectonic period is due to absolute NE movement and relative SW movement of Anatolia and surrounding area. This new tectonic model shows an adaptation with young magmatic and geothermal system of Western Anatolia as well. According to this new model, geothermal localities in the Aegean region and continuousness of geothermal systems which have been classified due to their heat sources can be explained.

Boron including fluids derived from altered oceanic crust and thick oceanic sediments, ascend towards the surface and change their isotopic composition by fractionation in different geological process (partial melting, crystallizations in the different environments), so that the boron occurs in different environments in differing amounts.

Geothermal systems which have deep circulation in Western Anatolia (Kizildere, Germencik, Salihli) have rather high amount of boron. These geothermal fluids which are hotter and have deep circulation interact with metamorphic rocks of Menderes Massif including some pegmatitic minerals. Generally these rocks have relatively low $d^{11}$B values and these values fit the low $d^{11}$B values of geothermal waters in contact with these rocks. According by, water-rock interaction appears to be as the main source for boron. Boron contents of geothermal waters having shallower circulation, like Pamukkale and Karahayit, are lower. On the other hand $d^{11}$B values of these waters are a little bit high due to their lithological differences. In geothermal systems having sea water contribution, higher $d^{11}$B values indicate that boron comes from sea water and also from water-rock interaction.

## 1. INTRODUCTION

The Western Anatolian and surrounding area underwent continental collisions which started in the Mesozoic (Sengor and Yilmaz, 1981). All of these tectonic events have had a part in shaping of Western Anatolia and surrounding. There are several papers that described the opening of the Aegean Sea and surrounding extensional areas of Western Anatolia as a backarc basin. The most common opinion about extension of Western Anatolia is westward escape of Anotolia (Sengör, 1985). According to this opinion, Anatolia moves to west related to the northward push of the Arabian plate. But plates velocity vectors increase from eastern Anatolia to the Aegean and Greece (Figure 1) and this contradicts the basic rule that the velocity field decreases moving away from the source area of the energy (Doglioni, et al., 2002). The biggest contradiction is how the Aegean Sea could open if the Anatolia plate is moving westward.

Other and a new model about extension of Aegean Sea and Western Anatolia have been suggested by Doglioni et al., (2002). According to this new model, the most prominent geodynamic factor in shaping the Western Anatolia is the northeast directed subduction of Africa underneath Greece and the Anatolia plate. Greece is overriding Africa along the Hellenic trench faster than Turkey along the Cyprus arc, it turns out that there is a positive velocity among Greece and Turkey in the hangingwall of the subduction zone. In fact, Greece is moving SW-ward above Africa faster than Turkey (Figure 1), which implies extension between Greece and Turkey in the Aegean area and western Anatolia (Figure 2a, b; Doglioni et al., 2002).

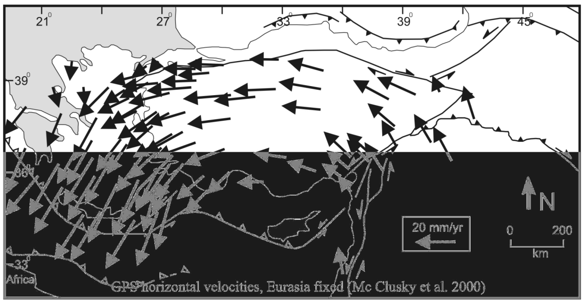


**Figure 1. GPS velocity field after McClusky et al. (2000) relative to Eurasia (Doglioni et al., 2002).**

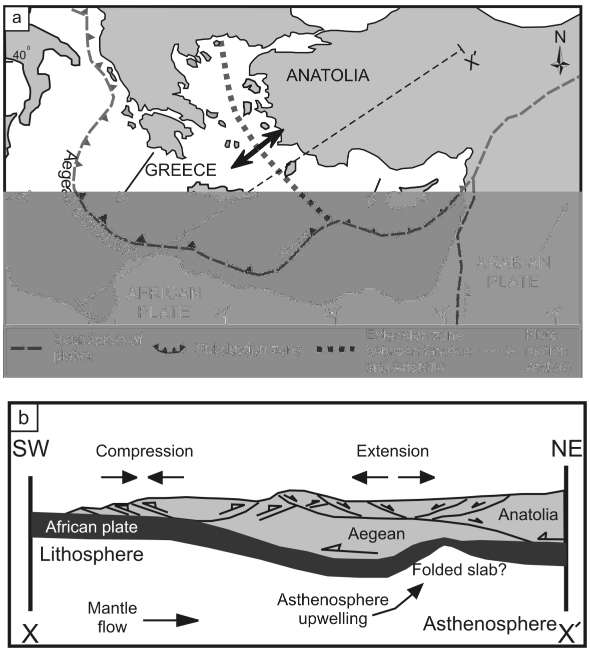


**Figure 2 (a) Considering a fixed Africa, Greece is overriding Africa faster than Cyprus and Anatolia. This implies extension between Greece and Anatolia (b) Schematic cross-section of overriding western Anatolia and Greece to African Plate. (Doglioni et al. 2002).**

## 2. GEODYNAMIC POSITIONS OF GEOTHERMAL SYSTEMS IN WESTERN ANATOLIA AND GREECE

Two main magmatic signatures occur in Western Anatolia since Miocene times. One of them is typical subduction-related, southwestward migrating Miocene to Present calk-alcaline volcanism and other one is Upper Miocene-Quaternary alkaline Na-rich magmatism (Benda et al., 1974; Yilmaz et al., 2001). Doglioni et al., (2002)'s new tectonic model shows an adaptation with this young magmatics and geothermal system of Western Anatolia as well.

The evolution of active geothermal systems in Western Anatolia goes to backwards up to pre-Neotectonic fossil geothermal systems. Active geothermal systems of Early Miocene which are fossil geothermal systems of Quaternary have evaluated and their primary, volcanic-magmatic heat source have changed to present tectonic-magmatic heat source (Figure 3a, b).

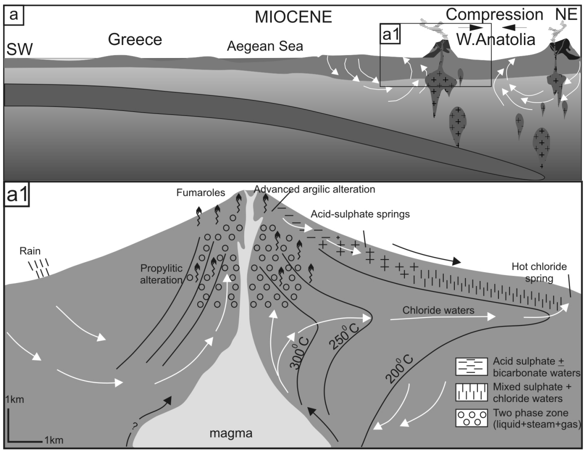


**Figure 3 (a), Western Anatolia's geothermal systems with active volcanic heat source in Miocene (Tokçaer and Savaşçin, (a1) conceptual structure of geothermal systems which have a volcanic heat source (Nicholson, 1993).**

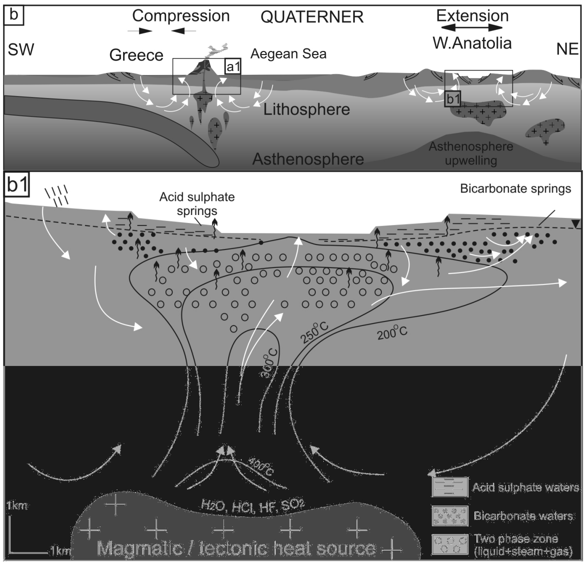


**Figure 3 (b), Greek Islands' geothermal systems with active volcanic heat source and Western Anatolia's geothermal systems with magmatic/tectonic heat source in Quaternary (Tokçaer and Savaşçin, (b1) conceptual structure of geothermal systems which have a magmatic/tectonic heat source (Nicholson, 1993).**

Geothermal systems are not common in Greece at the present time because of their compressional geodynamic position. Since northeast directed subduction of Africa underneath Greece, compression regime is dominated in Greece. Therefore, geothermal system of Greece is in the volcanic islands of Greece Island and their heat sources mostly depend on active volcanism like geothermal systems of Western Anatolia in the Miocene. Since Greece is moving SW-ward above Africa faster than Turkey, which implies extension between Greece and Turkey in the Aegean area. Western Anatolian geothermal systems have evaluated until Present times and their heat sources have changed from active volcanic to magmatic/tectonic heat sources depending on extension in Western Anatolia.

## 3. GEOCHEMISTRY OF GEOTHERMAL WATERS IN WESTERN ANATOLIA

The chemical compositions of the thermal waters are given in Table 1,2 and 3.

**Tablo 1. Chemical composition of thermal waters**

| Sample Location | T | pH | Ec | B | Si |
|---|---|---|---|---|---|
| | °C | | µS/cm | mg/l | mg/l |
| **Kizildere R1** | 76 | 9.6 | 7760 | 32.2 | 67.9 |
| **Kizildere KD13** | 94 | 9.8 | 6400 | 21.9 | 75.9 |
| **Karahayit** | 50 | 7.0 | 3100 | 2.0 | 18.2 |
| **Kaklik** | 35 | 7.4 | 2300 | 0.4 | 12.7 |
| **Ilik Pinar Seferihisr** | 32 | 7.9 | 397 | 0.1 | 31.4 |
| **Tuzla (Seferihisar)** | 53 | 6.5 | 35500 | 14.6 | 45.8 |
| **Aliaga** | 52 | 6.6 | 33400 | 14.5 | 33.7 |
| **Nebiler** | 58 | 7.5 | 1506 | 1.5 | 48.6 |
| **Pasa** | 47 | 7.3 | 2500 | 5.8 | 19.4 |
| **Dikili** | 74 | 7.2 | 2850 | 10.9 | 50.1 |
| **Asagibeyli** | 52 | 8.8 | 1000 | 0.2 | 27.6 |
| **Kestanbol** | 76 | 7.1 | 33000 | 12.3 | 49.1 |
| **Tuzla (Canakkale)** | 90 | 6.8 | 86800 | 25.4 | 46.3 |
| **Pamukkale** | 33 | 6.7 | 2520 | 0.9 | 17.4 |
| **Salihli mineral w.** | 24 | 6.8 | 1719 | | 16.7 |
| **Salihli K7** | 76 | 8.6 | 2450 | 43.0 | 102.0 |
| **Salihli K11** | 84 | 7.4 | 2290 | 51.2 | 111.0 |
| **Salihli K5** | 74 | 6.9 | 1820 | 52.1 | 89.0 |
| **Sard** | 50 | 6.2 | 1500 | 23.1 | 50.0 |

**Tablo 2. Chemical composition of thermal waters**

| Sample Location | $Li^+$ | $Na^+$ | $K^+$ | $Mg^{2+}$ | $Ca^{2+}$ |
|---|---|---|---|---|---|
| | mg/l | mg/l | mg/l | mg/l | mg/l |
| Kizildere R1 | 6.5 | 1450 | 208.5 | 0.2 | 0.2 |
| Kizildere KD13 | 4.5 | 1103 | 122.0 | 0.2 | 0.6 |
| Karahayit | 0.3 | 105 | 21.0 | 119 | 470 |
| Kaklik | 0.1 | 26 | 3.1 | 92 | 310 |
| Ilik Pinar Seferihisr | 0.0 | 26 | 8.8 | 2.8 | 48 |
| Tuzla (Seferihisar) | 10.3 | 6690 | 665.0 | 171 | 810 |
| Aliaga | 5.1 | 6340 | 230.0 | 570 | 650 |
| Nebiler | 0.3 | 182 | 8.9 | 13.0 | 60.5 |
| Pasa | 0.5 | 519 | 15.6 | 11.7 | 46 |
| Dikili | 1.3 | 485 | 35.0 | 8.0 | 42 |
| Asagibeyli | 0.0 | 183 | 2.4 | 0.4 | 17.9 |
| Kestanbol | 9.8 | 6150 | 645.0 | 56 | 860 |
| Tuzla (Canakkale) | 23.4 | 18090 | 1860 | 64 | 2800 |
| Pamukkale | 0.1 | 40 | 5.2 | 86 | 450 |
| Salihli mineral w. | 0.0 | 11 | 3.8 | 39.3 | 298 |
| Salihli K7 | | 635.0 | 79.5 | 2.3 | 16.5 |
| Salihli K11 | 4.4 | 470 | 64.2 | 9.3 | 49 |
| Salihli K5 | 3.1 | 335 | 44.0 | 17.5 | 88 |
| Sard | 1.5 | 161 | 22.5 | 21 | 180 |

These chemical compositions of the thermal waters in Western Anatolia are largely as a function of their host rocks. High temperature geothermal waters (Kizildere, Salihli) are mainly of Na–HCO3 type which interacted with Menderes Massif's metamorphic rocks. Other dominant water types are Ca-HCO3-Cl type waters which interacted with carbonate rocks and Na-Cl type waters which charged partly from sea. Lower temperature geothermal waters are of various types (Figure 4).

$^{18}$O and D isotopic compositions of these geothermal waters show meteoric origin (Figure 5). Most of these geothermal waters have similar compositions of local meteoric groundwater. Geothermal waters which have deep circulations (Kizildere, Salihli) have higher d$^{18}$O values because of water-rock interactions during the long residence time of waters. Sea water charged/mixed geothermal water of Western Anatolia (Tuzla, Aliaga, Seferihisar) have closer values to the SMOW (standard mean ocean water) than the others.

**Tablo 3. Chemical composition of thermal waters**

| Sample Location | $H_2CO_3$ | $HCO_3^-$ | $CO_3^{2-}$ | $SO_4^{2-}$ | $Cl^-$ |
|---|---|---|---|---|---|
| | mg/l | mg/l | mg/l | mg/l | mg/l |
| Kizildere R1 | - | 1940 | 708 | 736 | 146.2 |
| Kizildere KD13 | - | 1147 | 648 | 655 | 104.8 |
| Karahayit | 335 | 1196 | - | 842 | 26.3 |
| Kaklik | 50 | 610 | - | 746 | 25.2 |
| IlikPinar Seferihisr | 0 | 232 | - | 16.4 | 21.8 |
| Tuzla (Seferihisar) | 211 | 488 | - | 684 | 13760 |
| Aliaga | 484 | 866 | - | 1326 | 12800 |
| Nebiler | 37 | 500 | - | 303 | 42.6 |
| Pasa | 310 | 1574 | - | 125.5 | 47.2 |
| Dikili | 74 | 1062 | - | 434.5 | 86.7 |
| Asagibeyli | 0 | 67 | - | 303 | 29.9 |
| Kestanbol | 74 | 366 | - | 177.5 | 12800 |
| Tuzla (Canakkale) | 37 | 98 | - | 261.6 | 37550 |
| Pamukkale | 385 | 1049 | - | 610 | 12.2 |
| Salihli mineral w. | 159 | 1037.3 | - | 274 | 24.6 |
| Salihli K7 | - | 1275 | 228 | 34 | 105 |
| Salihli K11 | - | 1542 | - | 71 | 91.4 |
| Salihli K5 | 122 | 1213 | - | 90 | 50 |
| Sard | 226 | 1057 | - | 48 | 29 |

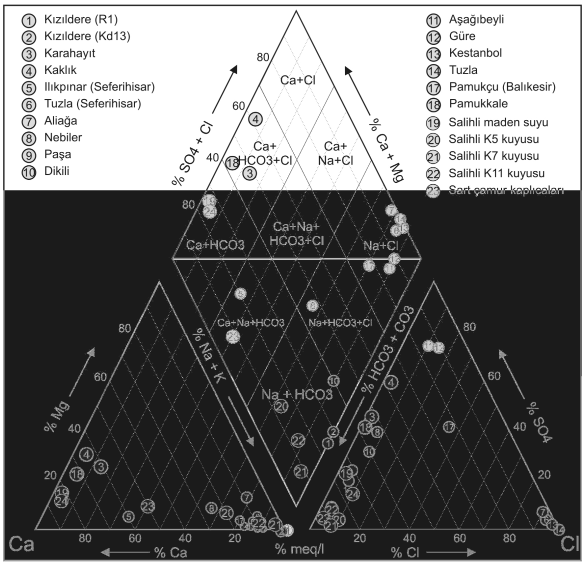


**Figure 4. Distributions of thermal waters of Western Anatolia are in a Piper diagram.**

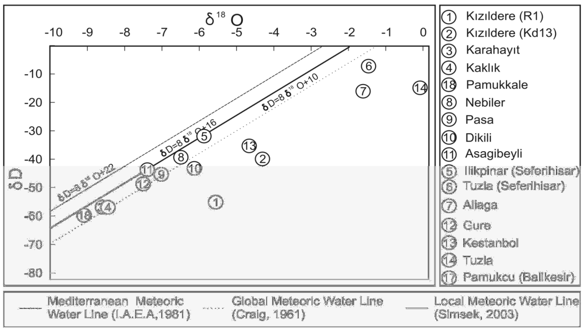


**Figure 5. Stable isotope compositions of the geothermal waters in Western Anatolia.**

### 3.1 Boron and Boron Isotopic Compositions of Western Anatolian Geothermal Waters

Geothermal systems of Western Anatolia especially have a deep circulation are include rather high amount of boron. It can be a few sources for boron. One of these sources of boron is water-rock interaction and the other one is orijinal parent magma fluids. For Western Anatolia region, boron mostly has been added to geothermal waters by water-rock interaction. Positive correlation between boron concentrations and temperature of thermal waters shows that boron concentrations increase with high temperature (Figure 6). This positive correlation support that water-rock interaction is the most important source for boron.

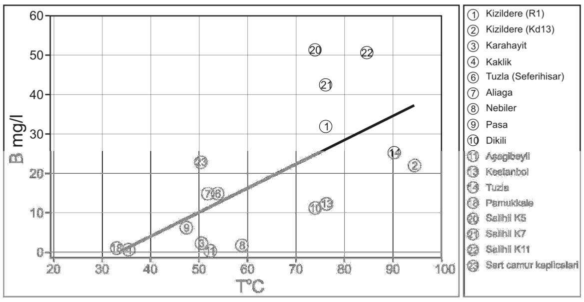


**Figure 6. Positive correlation between boron concentration and temperatures of thermal waters.**

Since the development of more accurate and precise techniques, boron isotopes have been started use in geochemistry.

Boron has two stable isotopes, $^{10}$B and $^{11}$B, with average relative abundances of approximately 20% and 80%, respectively. Boron isotope ratios are be referred to in terms of their d$^{11}$B, where;

$$\delta^{11}B = \left[\frac{^{11}B / ^{10}B_{örnek}}{^{11}B / ^{10}B_{standart}} - 1\right] \times 10^3$$

Based on favourable geochemical characteristics of boron – high solubility and mobility in aqueous solutions and incompatibility in most magmatic environments, the enormous relative mass difference of about 10 % of the two boron isotopes and the wide range of natural boron-isotope compositions (Palmer and Swihart, 1996).

Collected samples for boron isotopes were analyzed in Germany, GeoForshungZentrum (GFZ) by a negative thermal ionization mass spectrometry technique (NITIMS).

Boron isotopes are fractioned easily in different geochemical environment. If boron is coming to geothermal waters by water-rock interaction, there is no any fractionation. So that the geothermal water has a similar d$^{11}$B value to that of the rock (Palmer and Swihart, 1996).

d$^{11}$B value of geothermal waters in Western Anatolian are given in Table 4.

**Table 4. d$^{11}$B value of geothermal waters in Western Anatolian and d$^{11}$B value of rocks (Barth, 1993)**

| Location | d$^{11}$B | Lithology | d$^{11}$B values of rocks (Barth, 1993) |
|---|---|---|---|
| Kizildere R1 | 1,34 | metamorphics | -2 – (+14) ‰ |
| Kizildere KD-13 | 0,03 | metamorphics | -2 – (+14) ‰ |
| Pamukkale | 5,69 | limestone | -1 – (+30) ‰ |
| Karahayit | 0,08 | limestone | -1 – (+30) ‰ |
| Nebiler | -5,73 | Granodiorite | -30 – (-1) ‰ |
| Pasa | -0,33 | metamorphics | -2 – (+14) ‰ |
| Dikili-Çamurlu | -0,68 | Volcanic | -10 – (+5) ‰ |
| Kozak Asagibeyli | -4,71 | Granodiorite | -30 – (-1) ‰ |
| Kestanbol | 10,7 | Granodiorite | -30 – (-1) ‰ |
| Tuzla | 10,8 | Magmatic - volcanic | -30 – (+5) ‰ |
| Tuzla-Seferihisar | 3,79 | Flysch and Tertiary sediments | -25 – (+1) ‰ |
| Aliaga | 6,69 | Flysch and Tertiary sediments | -25 – (+1) ‰ |

As seen in Table 4, d$^{11}$B values of geothermal fluids are similar with d$^{11}$B values of host rocks. So, it can be seen clearly that water-rock interactions can contribute B to the thermal system more than original parent magma fluids. Only four thermal areas in this study (Tuzla, Canakkale, Serihisar –Tuzla and Aliaga) show different d$^{11}$B value from that of their host rocks. It can be explain by sea water mixing which has a high d$^{11}$B value (+40‰).

## 4. CONCLUSIONS

The evolution of active geothermal systems in Western Anatolia goes to backwards up to pre-Neotectonic fossil geothermal systems. Active geothermal systems of Early Miocene which are fossil geothermal systems of Quaternary have evaluated and their primary, volcanic-magmatic heat source have changed to present tectonic-magmatic heat source.

Chemical data reveal mainly two water types which originate from marine and nonmarine sources in this study. Non marine thermal waters have different water types but all of these waters have a similar $d^{11}B$ value to that of their host rocks. Boron isotopes, chemical data and good positive correlation with boron concentration and temperature of waters reveal that boron budget of geothermal waters have been controlled by the water-rock interaction more than original parent magma fluids. On the other hand, marine sources thermal waters have a different $d^{11}B$ value from that of their host rocks. Because these waters mixed with sea waters which has a high $d^{11}B$ value (+40‰).

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