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Structural Controls on Geothermal Activity in the East Anatolian Contractional Province-Turkey: Case Study: Muş and Varto Basins

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ABSTRACT

East Anatolian Contractional Province (EACP) of Turkey provides a natural laboratory for studying active tectonics, volcanism and related geothermal activity. There are over 50 thermal springs in the province that reveal a significant potential for the region. Quaternary volcanic centers (e.g. Nemrut, Süphan and Tendürek mountains) and active tectonic zones such as North Anatolian, East Anatolian, Muş and Varto fault zones are responsible for the deformation and recent morphology of the region. Formation of active tectonic structures along these fault zones such as strike-slip faults with pull-apart basins, extension cracks, thrust/reverse faults, caldera-forming faults and intrusion-related structures are the main controlling factors around the investigated areas. These structures create secondary permeability in reservoir units and widespread cover units of Solhan and Nemrut volcanism. Important surface manifestations (hot, cold and mineral springs) are associated with N-S directed extension cracks that form as a result of the interaction of the step-over and intersection areas of NW-SE strike-slip fault segments and the regional N-S compressional regime. There are many geothermal springs located in Muş and Varto basins where the surface temperatures of springs range from 20° to 60°C. In addition, geochemical geothermometer results show that the reservoir temperature of the region reaches up to 156°C. It is possible to use fluid of this temperature for power generation and /or district heating systems.

1. INTRODUCTION

Turkey has approximately 1,000 geothermal springs which are located in different regions of the country. With installed capacity, Turkey stands in the top four geothermal energy producer countries. While the installed power plants are concentrated in the Western Anatolian region, there are significant spring surface temperatures in other parts of the country that indicate additional geothermal potential. The study area is located on the eastern part of Turkey (Figure 1) referred to tectonically as the East Anatolian Contractional Province (EACP). Contrary to what is believed, the Eastern Anatolia Region has many potential geothermal resources and mineral waters. The region has nearly 90 known geothermal areas and Ağrı-Diyadin (66-78°C), Bingöl-Haciyan (40-68°C), Güroymak-Nemrut (46-59.5°C), Erzurum-Tekman (57°C), Hakkari-Sarıtaş (53°C) and Van (64-104°C) are the most important fields with geothermal potential (Akkuş et al., 2005).

One of the lower tributaries of the Euphrates, the Murat River basin is located within the boundaries of Muş and Bitlis provinces. The geothermal fields in the investigation area are studied in two adjacent basins which are known as the Varto and Muş basins. Kaynarca, Alagöztepe and Güzelkent geothermal fields are in the Varto Basin while Güroymak and Nemrut geothermal fields are located to the east of the Muş Basin (Figure 2). Surface temperatures of geothermal resources in Varto basin are range from 25 to 35°C while resources in the Muş basin are in the range of 36-60°C.

Determination of hydrogeological and tectonic properties of low-temperature fault-controlled sources is very important for recognition of the geothermal system. The definition of primary structural controls is a critical step for geothermal system identification. Also, heat transport mechanism, aquifer descriptions, structural controls, hydrogeochemical properties and geological environment are essential in defining and understanding the dynamics of a geothermal system. Faults and fractures are important surface indicators of hydraulic properties of rocks as permeability, hydraulic conductivity, transmissivity and porosity. Fracture aperture, distribution and networks, fault cores and damage zones are concepts in the control of structural elements that directly affect fluid circulation.

In contrast to the studies carried out in Western Anatolia, very few detailed studies have been conducted on the structural controls of geothermal systems in Eastern Anatolia. The information from the geothermal systems such as favorable zones for activity, primary controls, hydrogeology, fluid circulation and hydrogeochemistry have not been investigated in detail and sufficient information has not been obtained. The main purpose of this study is consideration of hydrogeological and hydrogeochemical properties, in addition to classifying of structural controls with emphasis on fault zone definition in the EACP.

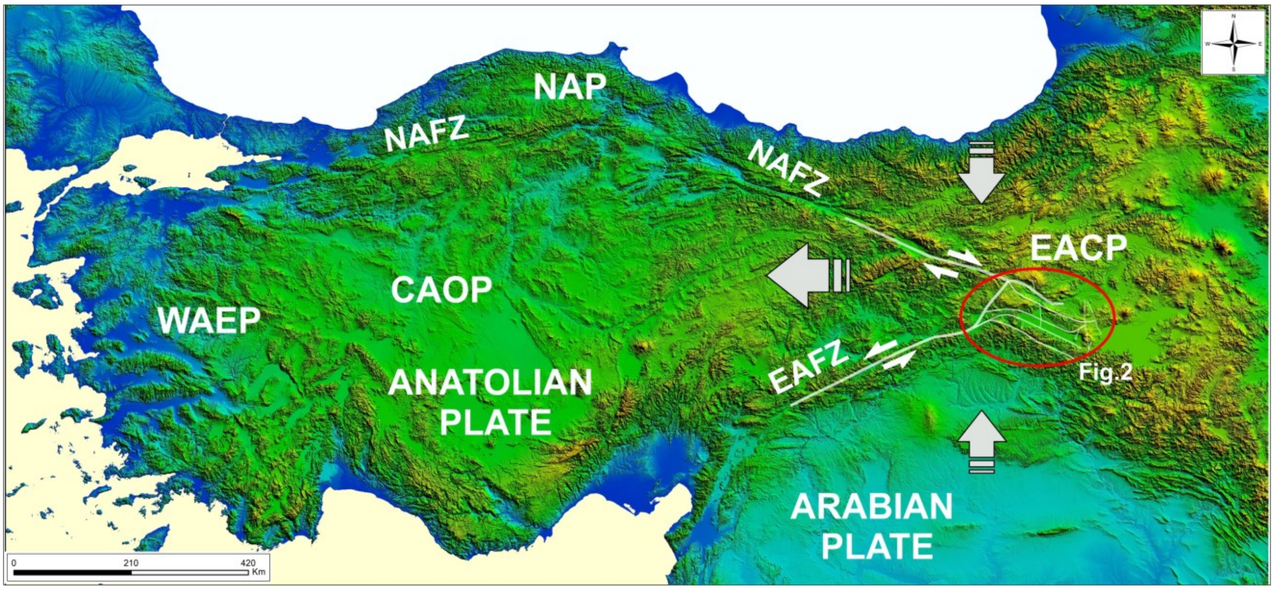

Figure 1. Location map of the study area (red-colored ellipse) with major neotectonic structures and main tectonic provinces of the Anatolia (Compiled from Şengör et al., 1985; Barka, 1992 and Bozkurt, 2001. WAEP: West Anatolian Extensional Province, CAOP: Central Anatolian Ova Province, EACP: East Anatolian Contractional Province, NAP: North Anatolian Province, NAFZ: North Anatolian Fault Zone, EAFZ: East Anatolian Fault Zone).

2. TECTONIC SETTING

The EACP is one of the most important neotectonic provinces of the Anatolian Plate. The region located on the deformation zone of the convergence between the Anatolian and Arabian plates. West Anatolian Extensional Province (WAEP), North Anatolian Province (NAP) and Central Anatolian Ova Province (CAOP) are other three neotectonic provinces of the Anatolia (Şengör et al., 1985; Barka, 1992; Bozkurt, 2001). These provinces are separated by North Anatolian Fault Zone (NAFZ) and East Anatolian Fault Zone (EAFZ). At the eastern termination of EAFZ, the Muş Basin bordered by the northern and southern fault segments of the Muş Fault Zone (MFZ) with its thrust-reverse and accompanying right-lateral strike-slip character. The MFZ forms morphologically unique compressional tectonic structures as being transpressional ramp basin (Figure 2). To the south of the MFZ, the Kavakbaşı Fault Zone controls the deformation on the basement rocks around the Bitlis Zagros Suture Zone (BZSZ) of Eocene age (Bozkurt, 2001). At the eastern termination of NAFZ, the Varto Basin, is formed under the control of three major segments of the strike-slip Varto Fault Zone (VFZ).

Quaternary volcanic activity is also important in the EACP where most of the Anatolian volcanoes and volcanic landscapes can be found such as Nemrut, Süphan, Tendürek and Ağrı mountains. Volcanic structures such as domes, sills, calderas and lava flows are present. Local extension due to regional N-S compressional regime interacting with other tectonics in region creates fissural volcanism and extension cracks which give a way for fluid circulation. Geothermal springs of the Muş basin have higher surface temperatures than the fields of the Varto Basin. One of the reasons is the presence of Quaternary young volcanism around the eastern part of the basin. Nemrut stratovolcano and Mazik and Germav domes are formed by Quaternary volcanism and occur at the extension zones called as “Güroymak” and “Nemrut”. Geothermal springs around that region are controlled by extension related fault and cracks.

2.1 Muş Basin

Under the influence of the transpressional regime, the Muş Basin acted as a ramp basin and consists of Quaternary and Pliocene volcanic and volcano-sedimentary units. The basin is bounded by the Oligo-Miocene and Eocene units from the north and the main units to the south while Bitlis Metamorphics are the basement of the basin. The contact between the basin fill and the basement units is the Muş Fault Zone (Yılmaz et al., 1987; Akay et al., 1989; Emre et al., 2012). Northern segments of the fault zone have reverse/thrust fault character and cross-cut relationships with NE-trending left-lateral strike-slip fault segments. There are also N-S directed lineaments which are the surface manifestations of local extension. Several strike-slip faults and reverse/thrust faults were determined in the southern segments of the MFZ. Reverse faults have approximately NNW trend, while strike-slip faults are NE and NW directed. Kinematic data indicates left-lateral displacements in NE-striking fault segments, while on NW-striking segments right-lateral motion was determined. Strike-slip faults allow water circulation and create important networks for groundwater flow and emerging cold-water springs (Uzelli, 2019).

In the east and west of the basin, several extensional zones such as Güroymak and Nemrut Extension Zones, were created by the compressional regime. The Murat lineament (ML), which is morphologically controlled the riverbed of the Murat River, is a potential extensional zone in the western side of the Murat Basin (Figure 2). This lineament has important mineral water resources on it. The other important extensional zones are called as Güroymak and Nemrut extensional zones and have important geothermal resources. At the same time, Nemrut volcanism reaches to the surface along the fissures of these extensional zones.

The fracture systems are secondary structural elements that control the fluid circulation in Nemrut and Solhan volcanics. Previous studies have also shown that fracture systems are concentrated around the domes and fracture permeability and geothermal favorability increase around the volcanic centers and extension zones (Siler et al., 2015). As well as geothermal springs, fracture and fault systems are distributed radially around the Nemrut caldera, Mazik and Germav domes around Güroymak region. Nemrut volcanics intensely fractured with tectonic conditions and fracture apertures are ranging between 5 and 20 cm. Caldera forming faults and extension related fractures create a suitable environment for geothermal activity in the Nemrut Caldera, around the Lake Ilı (Figure 3).

2.2 Varto Basin

The Varto basin is shaped by Varto Fault Zone (VFZ) where the faults intersect, terminate, step-over or bend formed favorable zones for geothermal activity. There are three major right-lateral strike-slip fault segments defined in the Varto basin in the south of the Bingöl Caldera (Herece and Akay, 2003). Leylekdağ, Çayçatı and Varto fault segments cut and displace the Pliocene Solhan volcanics and responsible for neotectonic deformation around the basin. There are important geothermal fields on the west and east of the Leylekdağ segment which is extending along with the mountain rise and Güzelkent and Alagöz settlements. The Alagöztepe geothermal field (Figure 4A) located on the step-over zone of the Leylekdağ segment. Stepping-over of the segment forms fissure-ridge type travertine deposits. Similarly, Güzelkent geothermal field (Figure 4C) occurs on the bending zone of the Leylekdağ segment.

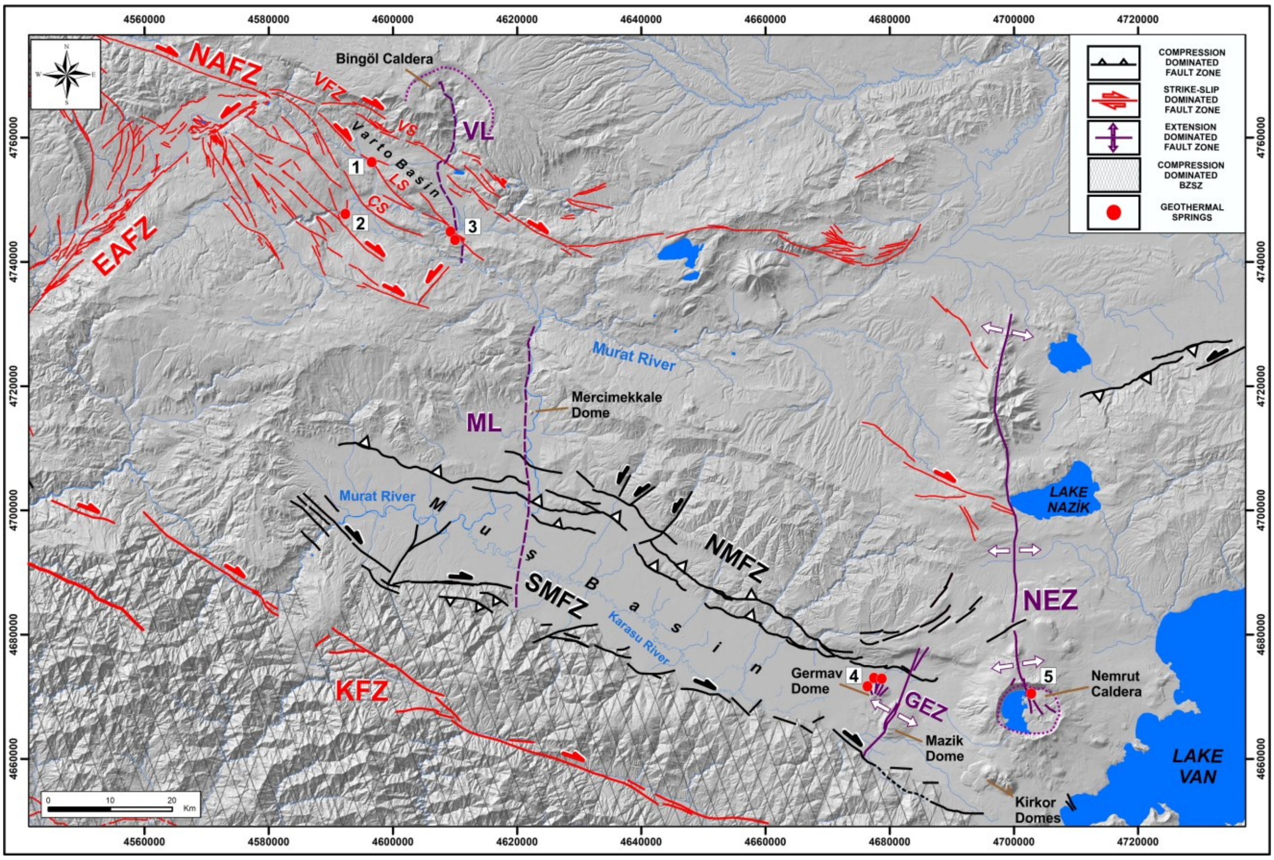

Figure 2. Primary structural controls of the study area with geothermal spring locations (Compiled from Göncüoğlu and Turhan, 1985; Şaroğlu and Yılmaz, 1986, Akay et al., 1989; Tarhan, 1991; Herece and Akay, 2003; Emre et al., 2012; Uzelli, 2019. NAFZ: North Anatolian Fault Zone, EAFZ: East Anatolian Fault Zone, VFZ: Varto Fault Zone, VS: Varto Segment, LS: Leylekdağ Segment, ÇS: Çayçatı Segment, SMFZ: Southern segments of the Muş Fault Zone, NMFZ: Northern segments of the Muş Fault Zone, KFZ: Kavakbaşı Fault Zone, VL: Varto lineament, ML: Murat lineament, GEZ: Güroymak Extension Zone, NEZ: Nemrut Extension Zone, 1: Güzelkent geothermal field, 2: Kaynarca geothermal field, 3: Alagöztepe geothermal field, 4: Güroymak geothermal field, 5: Nemrut geothermal field).

The right-lateral strike-slip fault segments lie to the south of Çayçatı segment. These parallel fault segments formed the southernmost geothermal field in the Varto basin. The geothermal activity has reached the surface where the main fault segment and the synthetic fault sets intersect (Figure 4B). Intersecting fault segments increased the geothermal activity and the permeability of rock units.

The Varto segment is the third segment of the VFZ. It deformed the relict structure of the Bingöl Caldera and cut and displaced the Varto Lineament (VL) which is an important local extensional zone in Varto basin (Figure 2). This segment formed numerous cold-water springs located on displaced blocks of the fault segments. Besides, since it is the closest fault segment to the Varto settlement, it is an important fault segment in terms of seismicity.

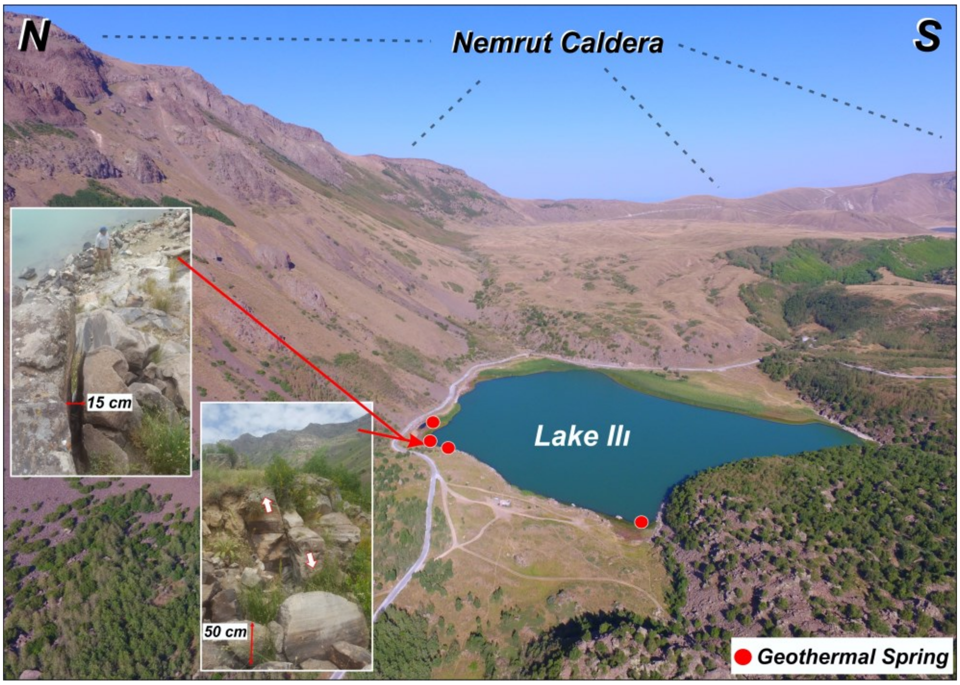

Figure 3. Drone-view of the inside of the Nemrut Caldera with showing locations of geothermal springs and fractures in volcanics around the Lake Ilı (Uzelli, 2019).

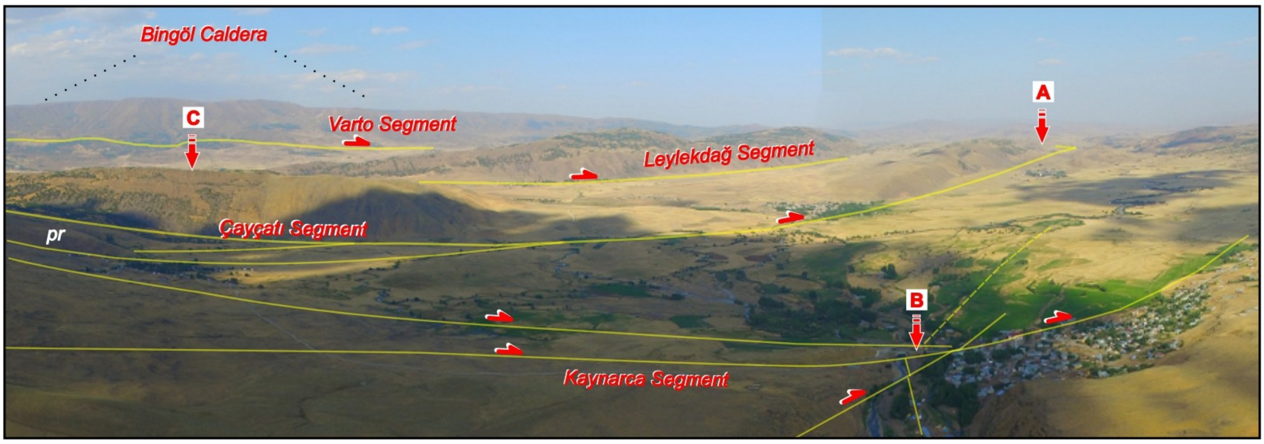

Figure 4. Structural controls of the Varto basin with geothermal spring locations (A: Alagöztepe geothermal field, B: Kaynarca geothermal field, C: Güzelkent geothermal field) (Uzelli, 2019).

3. HYDROGEOLOGY AND HYDROGEOCHEMISTRY

Permeability, porosity, fracture systems, lithological characteristics, stratigraphic properties, surface and groundwater resources, relations of the units are important parameters for the classification of hydrogeological units. Formations examined under four different groups as "Impermeable rock units", "Karstic aquifers", "Locally fractured aquifers" and "Porous and clastic aquifers". The definition of a karstic aquifer is used for important limestone reservoirs in geothermal systems with secondary permeability. Recrystallized karstic limestones, limestone blocks, dolomites and laminated quartzites are the most important rocks in terms of the hydrogeological and geothermal system located under the Tertiary units around Muş basin and Varto. The definition of porous and clastic aquifers describes the productive basin fillings formed by the Murat and Karasu rivers and current alluviums in the basin. Significant amounts of water are extracted from the wells drilled in these Quaternary units. The units that make up thick deposits in the Muş and Varto basins are cover rocks for the geothermal system even if they constitute important water resources.

The definition of locally fractured aquifer corresponds to the volcanics such as rhyolite-basalt, which can be supplied by fracture and fracture systems. The geothermal fluid in the Varto, Nemrut and Güroymak geothermal fields circulates through these volcanics and reaches the surface. Therefore, volcanism products reaching important thicknesses in the region are important in terms of hydrogeological aspects. Fracture and fracture systems increase secondary permeability, but in some regions, magmatic elements such as dykes and sills fill these fractures with causing significant heterogeneity in geothermal systems.

Non-aquifer impermeable rocks are composed of clay and ignimbrite-like lithologies, schist, gneiss, flysch and metagranites, which are impervious to fluid conduction, impermeable and cover. In general, the impermeable units corresponding to the basement units also impede fluid circulation in geothermal systems. The schists, gneisses and quartzites in the south of Muş basin have very small pore and network connections. Therefore, their primary permeability is very low. Also, clay and other alteration products made the situation worse in metamorphic units. Even though the old fracture and vein systems in the basement units affect the fluid circulation locally, they do not make a significant contribution to the current hydrogeological system.

When the physical properties of the waters in the region are examined, it is seen that their temperatures are at low levels. The highest temperatures were obtained in Ilıgöl, which is in the Nemrut caldera, with a temperature of approximately 60°C. The average surface temperature of thermal waters is 42.9°C, while the average temperature of cold waters and mineral waters is 17.3°C. The pH range determined an in-situ pH measurement varies between 6 and 9.6. Cold waters are in basic character while mineral waters are acidic. The pH values of thermal fluids vary between 6.2 and 8.5. EC values in the study area were measured between 50 and 187 µS/cm for cold waters around Varto, 205-630 µS/cm for cold waters in Muş basin, 543-5170 µS/cm for mineral waters, while values for geothermal sources were range from 1911 to 6070 µS/cm. The high EC values in the hot fluid are related to the water-rock interaction and the deep circulation of the fluid.

As can be seen in the Piper diagrams (Figure 5), the thermal and mineral waters of the Muş Basin were generally in the type of Na-Mg-HCO_3 and the cold waters were Ca-HCO_3 type. When Varto basin samples were examined, it was determined that cold waters were Ca-HCO_3 type, hot water and mineral waters were Na-Mg-HCO_3 and mixed type. All waters in the study area are in the immature waters section. This means that the waters are mixed with surface waters, even if they do not reach a partial water-rock balance and that the results of cation geothermometers cannot determine consistent reservoir temperatures for these waters. For this reason, it is more appropriate to use silica geothermometers which give more consistent results below 180°C than the results of applied geothermometer equations. Estimated reservoir temperatures of the waters in the study area according to these geothermometer calculations are range from 45.7°C to 156°C.

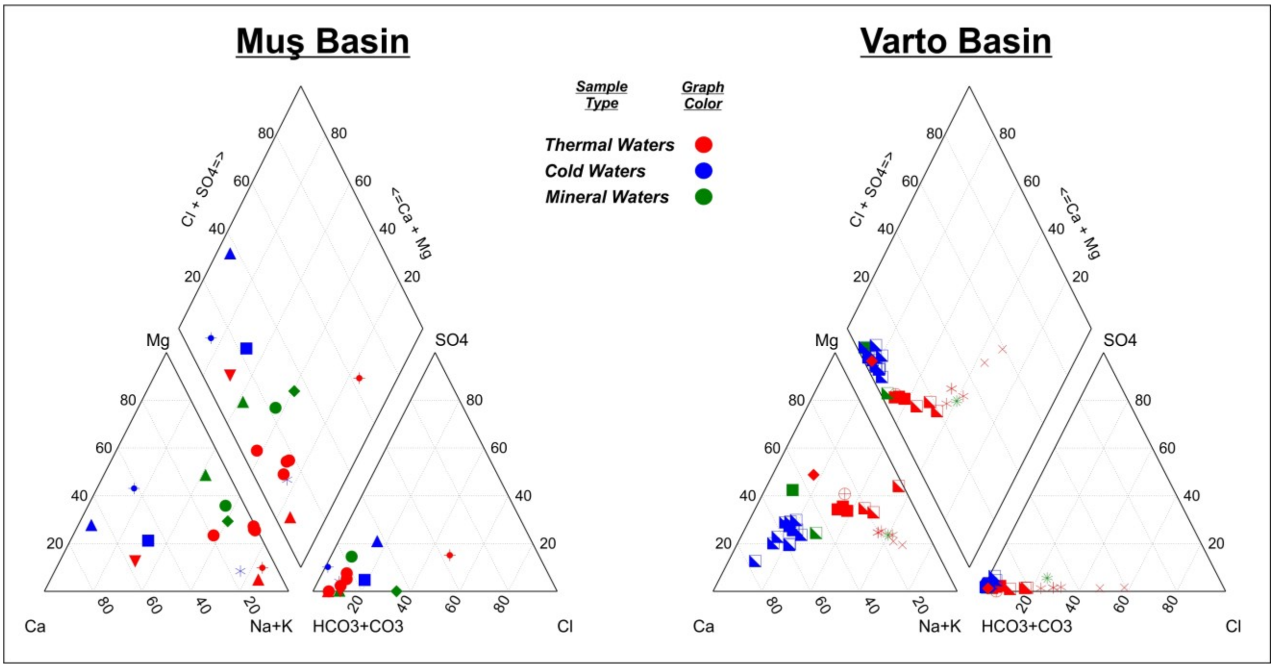

Figure 5. Chemical analysis of water samples in the study area plotted on Piper diagram (Uzelli, 2019).

The $\delta^{18}O$ values are range from approximately −9 to −12‰ and δD values range approximately from −61 to −82‰ in the study area. As seen from Figure 6, samples from the Varto basin have lowest $\delta^{18}O$ and $\delta^{2}H$ values. Water in Varto is fed by humid air bodies with low isotope differentiation and isotope content. At the same time, these waters are fed from higher topographic feeding areas compared to the waters in the Muş basin. Almost all the waters are in meteoric origin because they are located near or over the Global Meteoric Water Line (GMWL-Craig 1961).

4. RESULT AND DISCUSSION

Hydrothermal, tectonic and magmatic conditions cause different problems in geothermal systems due to different control mechanisms. For this reason, different opinions about the classification of geothermal systems are presented with recent studies. In this study, geothermal resources are classified based on structural controls, lithology, fluid properties and heat transfer regime.

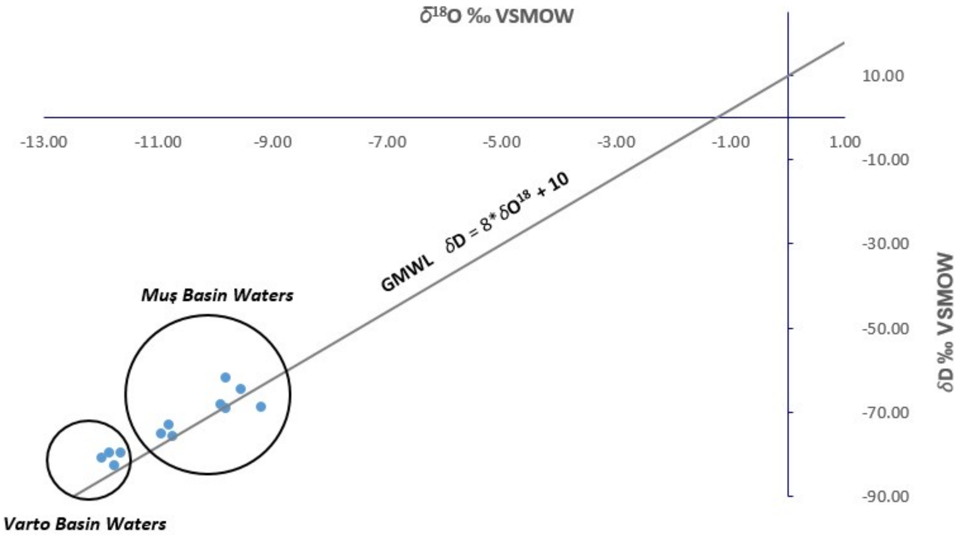

Figure 6. Stable isotope compositions of the waters in Muş and Varto basins (Uzelli, 2019).

Table 1. General classification of geothermal fields based on geological, hydrogeological and structural data (Uzelli, 2019).

REGION	WESTERN MUŞ BASIN	EASTERN MUŞ BASIN NEMRUT -GÜROYMAK	VARTO BASIN
Tectonic Environment	Transpressional ramp basin	Extension zone with volcanism	Strike-slip fault zone
Heat Transfer	Convection	Convection	Convection
Fluid Origin	Meteoric	Meteoric	Meteoric
Fluid Transport	Fault controlled– Shallow	Fault controlled – Deep	Fault controlled – Deep
Primary Structural Control	Muş Fault Zone	Nemrut and Güroymak Extension Zones	Varto Fault Zone
Suitable Location for Secondary Permeability	Bends and step overs of strike-slip faults	Extension cracks, caldera faults, dome structures, volcanic centers	Bends and step overs of strike-slip faults, intersecting faults, fault tips
Heat Source	Geothermal gradient	Relict magma chambers	Geothermal gradient, shallow magma chambers
Reservoir-Aquifer	1-Karstic limestones (basement rocks)	1-Fractured volcanic rocks 2- Karstic limestones (basement rocks)	1-Fractured volcanic rocks 2- Karstic limestones (basement rocks)
Cover Rocks	Tertiary basin fill deposits	Quaternary ignimbrites	Pliocene volcano-sedimentary units and Quaternary basin fill deposits

In general, the groundwater circulation system in the basins consists of two main aquifers. These are deep karstic limestone aquifers and shallow aquifers in Neogene and Quaternary units. It is thought that there could be shallow residual magma chambers located around Nemrut and Güroymak extension zones and main structural controls of geothermal systems are predominantly strike-slip and compressive tectonic environments. Muş basin is a structurally controlled ramp basin where the transpressional regime is observed. Similarly, Varto is a basin formed under control of the Varto Fault Zone and forming geothermal resources as a result of structural controls. The geothermal system which is connected to the Nemrut volcanism in the east of the Muş basin is predominantly under the control of the extension zones.

According to the fluid properties, all the waters indicate a meteoric origin as supported by isotopic data. The waters in the Muş basin are shallower and younger than the Varto basin. The waters in Varto were able to reach deeper through structural controls and were exposed to more water-rock interactions. As a result, fluid circulation is provided with structural control and in terms of infiltration, precipitation and surface flows have the potential to provide fluid presence and circulation in geothermal systems. Based on the findings of the study, some direct applications can be made in existing geothermal fields which do not have high temperatures and whose surface temperatures vary between 30° and 65°C. Geothermometer results indicate a maximum reservoir temperature of 156°C. These reservoir temperature values are very suitable for power generation and residential heating systems. In addition, a stronger economy will be provided with the cultural tourism in the region through applications such as greenhouses, thermal tourism and swimming pools.

5. ACKNOWLEDGMENTS

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