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Structural controls and hydrogeochemical properties of geothermal fields in the Varto region, East Anatolia

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Abstract: Varto and the surrounding region have important geothermal fields, developing in strike-slip tectonic setting in East Anatolia, which resulted from the collision of the Arabian and Eurasian plates. The main structural elements in the area are the NE-trending sinistral and NW-trending dextral strike-slip fault segments and N-S trending extension zones. In order to determine fault-controlled geothermal circulation, it is very important to fully characterize the structural elements in these complex environments. The widely distributed volcanic rocks have fracture and crack systems that play an important role in surface infiltration, geothermal fluid, and groundwater circulation. Especially in areas where the fault segments intersect, hot springs outlets and natural resources easily come to the surface. In order to understand the flow paths of geothermal fluid along the faults in these geothermal systems, it is necessary to determine the stress state of the faults and to map the distribution of the structural elements. For this reason, we conducted a detailed study on the Varto Fault Zone, which has important geothermal fields in Eastern Anatolia. We present conceptual models of the geothermal fields in the Varto region that show favorable geothermal activity on the intersecting fault segments, fault bends, step-overs, and accompanying fracture-crack sets. As a result, we emphasize that the planes of strike-slip faults in transtensional areas are more favorable for secondary permeability and enhances the geothermal fluid circulation, and this can be supported by hydrogeochemical data.

Key words: Structural geology, Eastern Anatolia, geothermal energy, Varto, triple junction

1. Introduction

Energy is among the leading problems of all countries in the world today. The most important reasons for this are population growth, industrialization, and rising living standards. A large part of the energy requirement, which has been increasing rapidly all over the world, is met by fossil fuels. The environmental problems created by fossil fuels, especially due to their effect on global warming, are increasing their orientation to renewable energy sources. Among the renewable energy sources, geothermal energy is a source originating from the internal heat of the world, and it will become the most important energy source in the near future with its 24-h applicability, sustainability, and environmental friendliness.

In order to define the geothermal system, we need to know most about structural controls in addition to stratigraphy, lithology, regional geology. In addition to areas where the geothermal gradient is known to be high due to magmatism (Karaoğlu et al., 2020a, 2020b), deformation zones related to intersecting faults, transfer zones, fault terminations, and pull-apart basins are the most favorable zones for geothermal activity (e.g., Faulds and Hinz, 2015). In recent years, many studies have been conducted to describe the relationships between structural controls and geothermal activity, and generally favorable fault segments for geothermal resources have been studied (Faulds et al., 2010a; 2010b; 2011; Moeck and Beardsmore, 2014; Faulds and Hinz, 2015; Siler et al., 2015; Uzelli et al., 2017).

This is especially important in the East Anatolian Region of Turkey, where most of the geothermal hot springs are fault-controlled. The region is characterized

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by strike-slip faults, reverse faults, extension cracks, and volcanic environments, which were generally formed under the regional compressional tectonic regime. While the main cause of the compressional tectonism in the region is the convergence between the Anatolian Plate and the Arabian Plate, the North Anatolian and East Anatolian transform faults in the region are the main elements of the strike-slip tectonic regime. For this reason, it is possible to see structures such as thrust and extensional cracks as well as pressure ridge, pull-apart, and step-over/bending areas in the study area.

The Varto Fault Zone (VFZ) is located in the east of the intersection point of the East Anatolian Fault Zone (EAFZ) and the North Anatolian Fault Zone (NAFZ) (Figure 1a) and together they formed the tectonic structure defined as Karlıova Triple Junction (Karaoğlu et al., 2017). Around this region, these two transform faults and VFZ caused deformation and initiation of volcanism. The study area in Varto is within the VFZ (Figure 1), which provides a structurally favorable setting for geothermal activity.

The main purpose of this study is to obtain new scientific data about the structural controls and hydrogeochemical properties of the geothermal fluid in the Varto region and to provide important inputs to future geothermal studies.

2. Methodology

Geological and hydrogeological maps of the study area were compiled for revision in field studies. In site selection, existing geothermal springs and surface anomalies related to the geothermal activity such as alteration and travertine formations were considered. As a result, three important geothermal fields have been selected for investigation and providing new data in Varto and environs. These fields are Kaynarca (Figure 2a), Güzelkent (Figure 2b), and Alagöztepe (Figures 2c, 2d) geothermal fields.

This fieldwork includes the determination of kinematic analysis of faults, morphological indicators, and hydrogeochemical sampling process. The manual lineament identification was applied based on remote-sensing analysis of digital elevation models created from 1/25000 scale topographic maps and drone imagery. Fault-kinematic data from structures are processed in the Win-Tensor program which is designed for paleostress reconstruction by Damien Delvaux (Delvaux and Sperner, 2003). The stress tensor calculations are made with Function-2 based on Angelier's reduced stress tensor concept. In total, 27 slip data and fracture data were collected from 4 different locations. All fracture data were collected around the hot spring outlets and processed in kinematic analysis.

For the investigation and comparison of the hydrogeochemical characteristics, four geothermal springs and a mineral water source were monitored from 2017 to 2019 in the study area. The concentrations of major ions were determined in the water samples. During the field surveys, some physical parameters of the geothermal fluid, including temperature (°C), pH value, and electrical conductivity (EC, µS/cm) were measured in-situ with an HQ40d. The samples of groundwaters and geothermal fluids were collected in bottles (LPDE) and analyzed by the Environmental Development, Application and Research Center and Geothermal Energy Research and Application Center within the İzmir Institute of Technology (IZTECH). Ion chromatography (IC) is used for the analysis of both anions and cations in water samples.

Finally, in order to define the properties of the geothermal system in the study area, we compile a GIS database of the geothermal and cold water sources, structural data, geological, and hydrogeological features.

3. Geological and hydrogeological properties of study area

3.1. Stratigraphy

The stratigraphic succession in the Varto region consists of Pre-Tertiary basement (Bitlis metamorphics), Eocene fluvial sediments, marine Oligocene-Lower Miocene deposits, Upper Miocene-Pliocene sandstones and conglomerates with intercalated volcanic products, Quaternary deposits, and volcanic rocks (Figures 3, 4). Within the scope of this study, the geological maps of previous studies (Tarhan, 1991; Herece and Akay, 2003) were used as a base map and detailed with field observations, especially in regions with geothermal resources.

The oldest units in the Varto region are represented by the Precambrian basement rocks belonging to the Bitlis metamorphics, which consist Middle-Upper Devonian/Upper Triassic platform deposits with an angular unconformity (Perinçek, 1980; Perinçek and Özkaya, 1981; Çağlayan et al., 1983; Göncüoğlu and Turhan, 1983; Şaroğlu and Yılmaz, 1986). Bitlis metamorphics contain Precambrian gneiss, amphibolite, eclogite, and schists.

The Miocene Adilcevaz formation has a wide distribution between the Muş Basin and Varto (Demirtaşlı and Pisoni, 1965). The unit consists of limestone member, algal sandstone-conglomerate-marl, and thin medium bedded conglomerate sandstone alternations (Akay et al., 1989). The unit, which does not outcrop in the study area, is covered by Pliocene units in the stratigraphic sequence.

There have been many important studies about the genesis of the collision-related volcanism around the Varto region (Pearce et al., 1990; Notsu et al., 1995; Buket and Temel, 1998; Yılmaz et al., 1998; Hubert-Ferrari et al., 2009). The volcanism products in the study area are associated with the Solhan volcanism and explosive eruption of the Varto Caldera (Karaoğlu, 2020). The

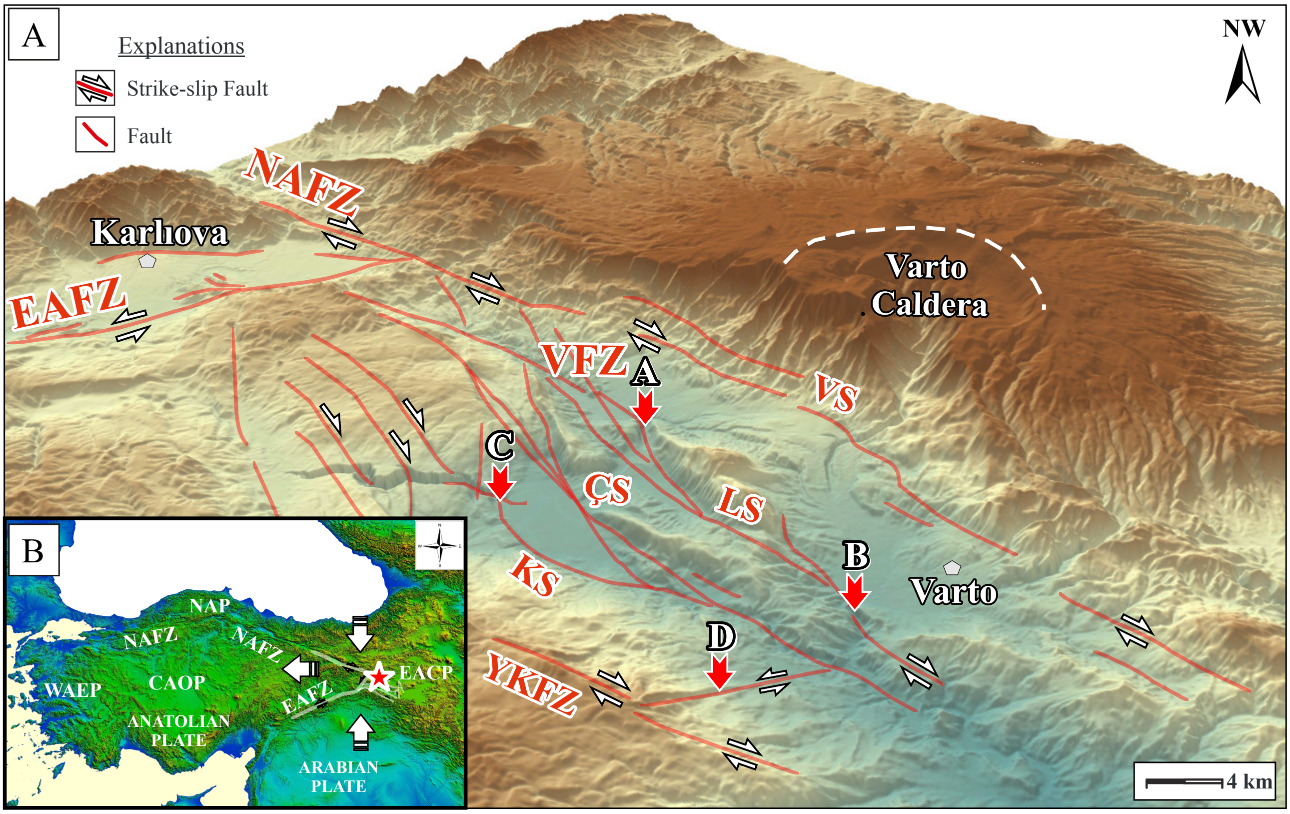

Figure 1. a) Digital elevation model of Varto region with main fault segments (A: Güzelkent geothermal field, B: Alagöztepe geothermal field, C: Kaynarca geothermal field, D: Karameşe mineral water, VS: Varto Segment, LS: Leylekdağ Segment, ÇS: Çayçatı Segment, KS: Kaynarca Segment, YKFZ: Yorgançayır-Kaynarca Fault Zone), b) location map of the study area with major neotectonic structures and tectonic provinces of the Anatolia (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).

Solhan formation can be widely observed around the Varto, with volcanic rocks and dome formations (Yılmaz et al., 1987; Akay et al.,1989). The latest study shows that volcanic rocks of this region are grouped into three phases of activity (Karaoğlu et al., 2020a): the early phase (Solhan volcanism; ~7.3–4.4Ma), middle phase (Turnadağ and Varto volcanism; ~3.6–2.6 Ma), and the late phase (Özenç and Muş volcanism; ~2.6–0.5 Ma). Within the scope of this study, the Solhan formation and volcanic rock member were mapped in accordance with the study of Herece and Akay (2003), and the geological age range was revised according to Karaoğlu et al. (2020a).

Solhan formation shows a simultaneous sediment deposition with the Lower Miocene-Pliocene Zırnak formation (Akay et al., 1989). For this reason, lacustrine sediments, pyroclastics, sandstone claystone, ignimbrite, and lavas are found in the widely distributed succession. The Zırnak formation generally consists of river terraces and layers of conglomerate, sandstone, marl, claystone, and limestone around Varto (İlker, 1966; Akay et al., 1989).

The Pliocene-Lower Pleistocene Yolüstü formation composed of terrace sediments between the Varto settlement and the Leylekdağ segment (Tarhan, 1991). The unit covers the Zırnak and Solhan formations with angular unconformity and fills the depositional environments between the segments of the VFZ.

Quaternary units in the study area are travertines, sediments belonging to old landslides near Varto Caldera, and alluviums accumulated along stream beds. The material carried by the Murat River, Mengel Stream, and Kaynarca River also form sediment cover up to 400–500 m around the rivers. Alluvial fans and talus located along the basin boundaries are other Quaternary units.

3.2. Hydrogeology

Literature describing the hydrogeological properties and hydrology of the Varto Region is very limited. The most detailed research about the hydrogeology of the Varto Region is provided in Baba et al. (2010), and cold and hot waters in Varto are examined in detail in terms of hydrogeological and hydrogeochemical aspects. Within

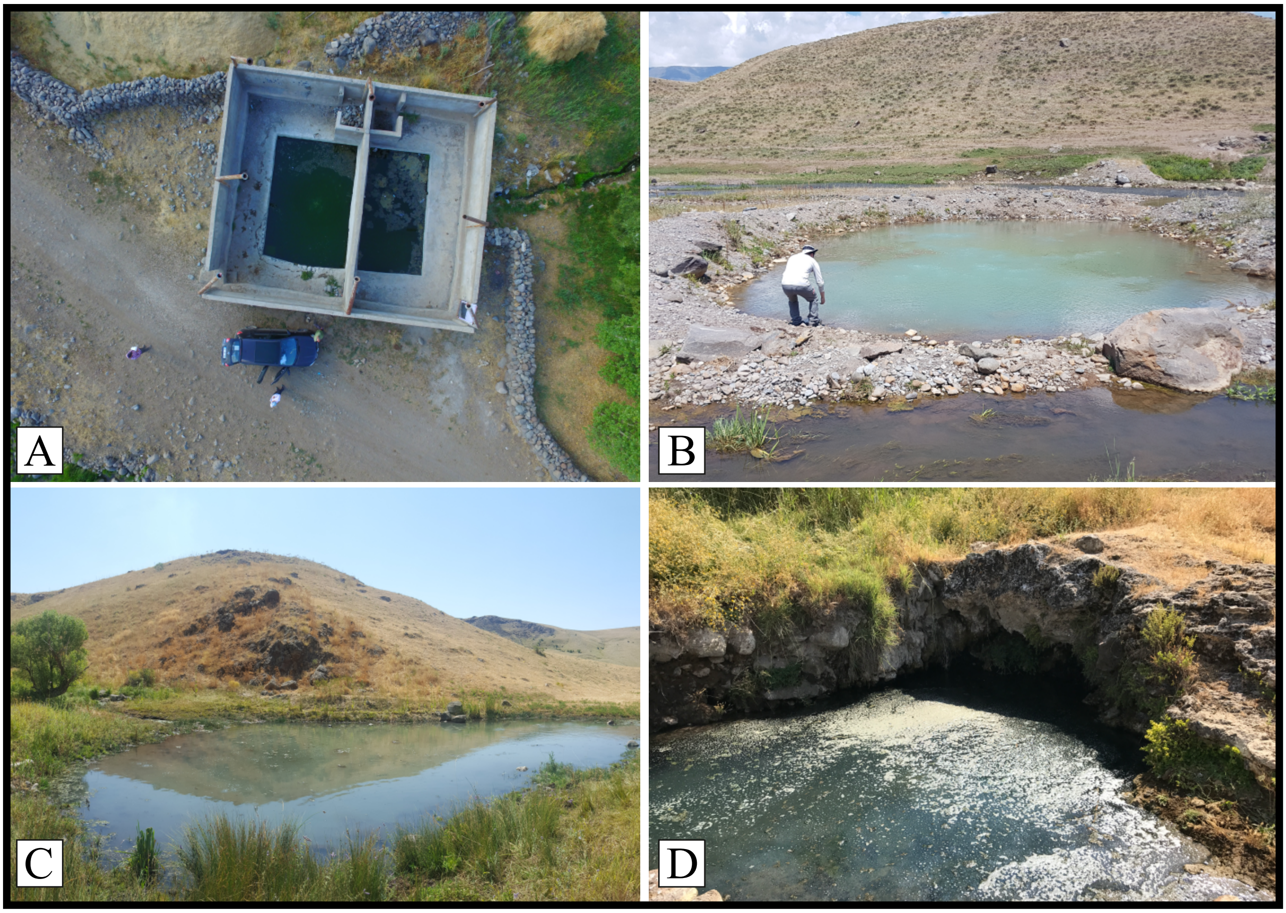

Figure 2. a) Primitive spa application of Kaynarca hot spring, b) Güzelkent hot spring, c) Alagöztepe-I hot spring, d) Alagöztepe-II hot spring.

the scope of this study, the hydrogeological features of the lithological units in the region were determined by considering the previous studies and the observations made around Varto.

In the light of field observations, the formations examined under five different classes: "non-aquiferous confining rock units", "highly productive fractured karstic aquifers", "moderately productive fractured aquifers", "moderately productive porous aquifers", and "highly productive porous aquifers". The definition of "karstic aquifer" has been used for reservoirs important for geothermal and hydrological systems with secondary permeability in the study area. The definition of "porous aquifers" defines the clastic basin fillings formed by rivers and used alluviums. While "fractured aquifer" defines volcanic rocks where water can be supplied with fracture and fissure systems, "non-aquiferous confining rocks" consist of impermeable and capping clay and ignimbrite lithologies as well as schist, gneiss, and metagranites.

The basement units have very important rocks in terms of hydrogeological and geothermal potential. However, these units do not outcrop in Varto and its surroundings, as in the southern regions. The basement units below the Miocene units have the potential to be reached by deep drilling. The Paleozoic-Lower Mesozoic karstic limestones in metamorphics (Göncüoğlu and Turhan, 1985), are highly productive fractured karstic aquifers in the basement units.

Limestones belonging to the Adilcevaz formation are another important unit that has reservoir characteristics in Varto and environs. Porosity values in the range of 2.5%–16.5% were obtained from thin sections taken from Adilcevaz limestones (Sözeri, 2007). It is known that the most important factor affecting the porosity values is the non-resistant areas with fossiliferous levels in the unit and well-developed crack systems. The specified porosity values and the existing water wells seen in the field are proof that this unit is a moderately productive fractured aquifer. The aquifer feature of this unit is very important

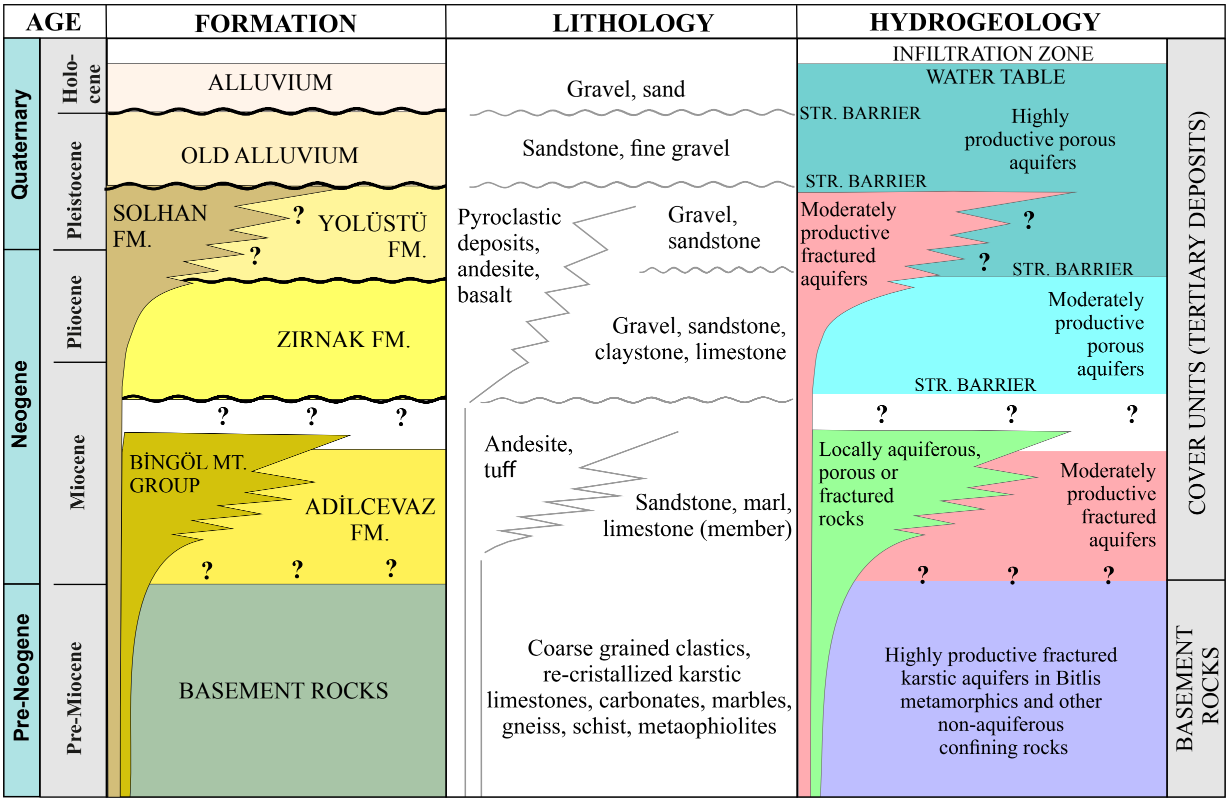

Figure 3. Stratigraphy-hydrogeology correlated columnar section of the Varto region ("Str." is an abbreviation of "Stratigraphic", Göncüoğlu and Turhan, 1985; Akay et al., 1988; Akay et al., 1989; Tarhan, 1991; Herece and Akay, 2003; Karaoğlu et al., 2020a).

for future geothermal research in the southern Varto region.

There are many natural springs formed around volcanic units around the Varto. The presence of cold water springs with high flow rates (1–150 L/s; Baba et al., 2010) indicates that a productive aquifer is present in at the near-surface volcanic environment. Widespread volcanic rocks with favorable secondary permeability conditions cropped out in the region are characterized as a moderately productive fractured aquifer. However, impermeable volcanic levels containing ignimbrites and tuffs are classified as non-aquiferous confining units.

The Zırnak formation has the capacity to store a significant amount of groundwater. Considering in more detail the lithological properties of the Zırnak formation, lateral transition with the Solhan formation causes the formation of confined-perched aquifers in some areas, so water can be obtained even from shallow wells. There are shallow wells that provide drinking water from the Zırnak formation. Granular and dendritic deposits of the formation are hydrogeologically characterized as a moderately productive porous aquifer.

The Yolüstü formation and alluvium units overlying the Pliocene units are aquifer units containing significant amounts of water. Recent clastics and coarse-grained riverbed sediments are usually gravel and block-sized and are distributed along riverbeds. These materials are unconsolidated and have high permeability-porosity properties. Porous sandstones form local artesians, especially in areas with the talus and around Varto. In addition, many cold springs emerge along fault scarps and fracture zones (Baba et al., 2010).

Fractured volcanics and karstic limestones in the basement units, which are hydrogeologically in the character of a reservoir, contain the geothermal fluid in the geothermal system. Geothermal fluids reaching the surface through faults from karstic and fissured aquifers formed geothermal fields. The Eocene-Oligocene units and Quaternary deposits act as basin fill and impermeable cover in geothermal systems in the entire study area. Travertine deposits are also seen around the Alagöztepe hot springs.

4. Structural controls of the geothermal fields

The Anatolian plate between the NAFZ and the EAFZ moves westward from Eastern Anatolia, in the collision zone between the Arabian and Eurasian plates (Dewey et al., 1986; Barka, 1992; Okay and Tüysüz, 1999; Bozkurt, 2001). As a result of the deformation of neotectonics, four different neotectonic provinces were formed. These are the East Anatolian Contractional, the North Anatolian, the Central Anatolian 'Ova', and the West Anatolian Extensional provinces (Bozkurt, 2001).

The East Anatolian Contractional Province (EACP) is the most characteristic of these regions regarding its features (Şengör et al., 1985; Bozkurt, 2001). While continental collision-related tectonics between the Arabian-Anatolian plate resulted in a compressional tectonic regime in the region, transform fault zones cause a strike-slip tectonic regime. In this tectonic environment, the NAFZ intersects with the EAFZ and the VFZ near Karlıova to form a "Triple Junction Structure" (Karaoğlu et al., 2017).

The VFZ, which includes the Varto, Leylekdağ (also called as Leylekdağı) and Çayçatı fault segments (Herece, 2008; Figure 4) is an active dextral strike-slip fault zone (Emre et al., 2013). The Varto earthquake of 19 August 1966 and 20 August 1966 (M: 6.8 and M: 6.2) caused casualties (2394 were killed and up to 1500 people were injured) and affected settlements around the Varto (Ambraseys and Zatopek, 1968; Wallace, 1968).

In the literature, many researchers conducted numerous investigations about this fault zone and presented different opinions. These studies were generally carried out to establish the connection between the VFZ and the NAFZ (Ketin, 1969; 1976; Şengör, 1979; Şengör et al. 1985; Şaroğlu, 1988; Barka, 1992; Gürboğa, 2016) to define the fault segments around the Varto fault zone and Karlıova triple junction with regional stress conditions (Herece and Akay, 2003; Herece, 2008; Hubert-Ferrari et al., 2009; Sançar et al., 2015; Karaoğlu et al., 2017; Sançar et al., 2018) and magmatism (Karaoğlu et al., 2018; Karaoğlu 2020a). In addition, some of the recent studies with fluid-solid interactions and fluid circulation models show that permeable faults are important factors affecting the geothermal system (Karaoğlu et al., 2019).

The mechanism of the geothermal activity in the study area is primarily controlled by the dextral strike-

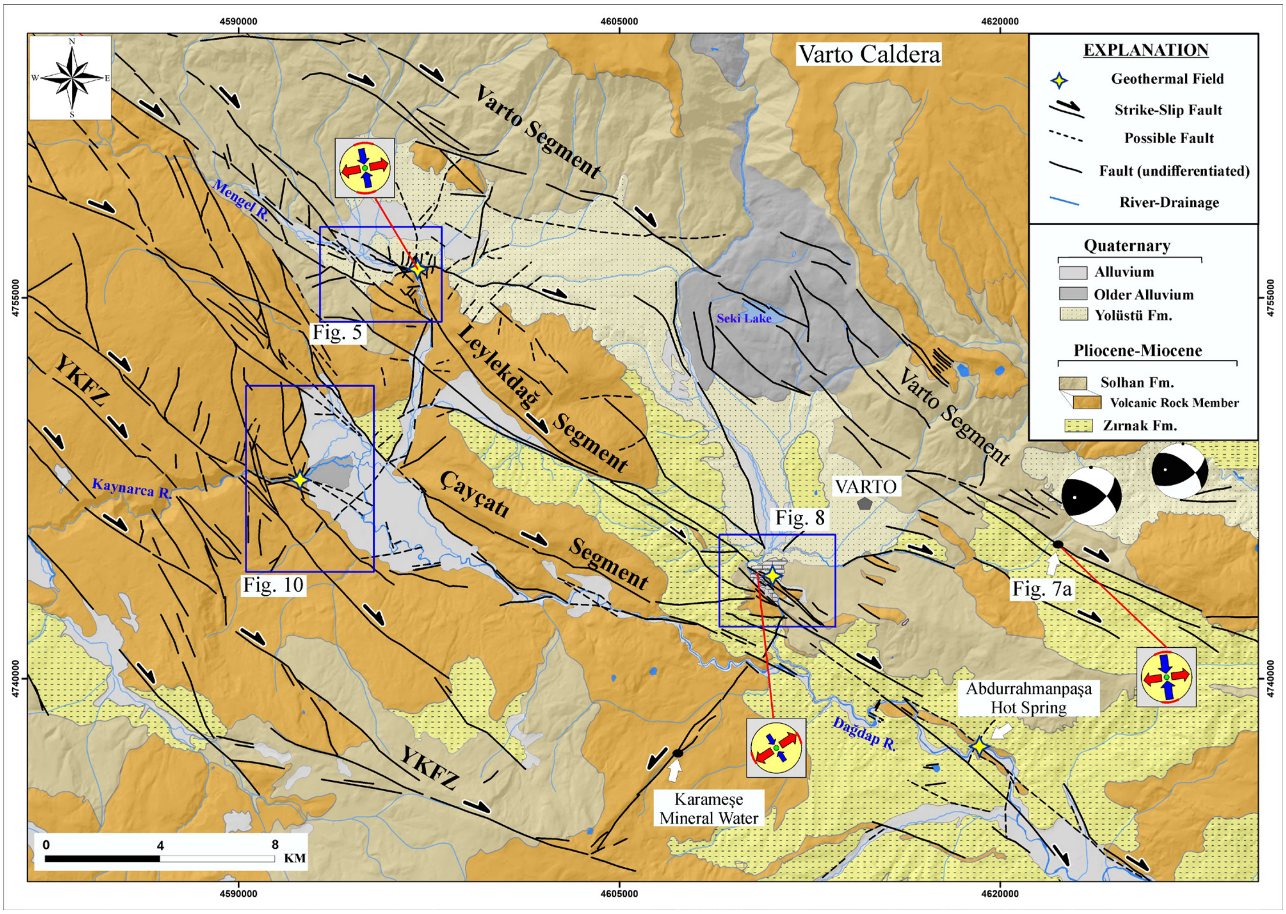

Figure 4. Geological map of the Varto and surroundings (Tarhan, 1991; 1997; Herece and Akay, 2003; Emre et al., 2013; Uzelli, 2019) with the focal mechanism solutions (McKenzie, 1972 and Tan et al., 2008) and stress symbols.

slip VFZ (Figure 4). Distribution of the hot springs is closely related to the lineaments of fault segments. In this section, observations made in Güzelkent, Alagöztepe (I-II), and Kaynarca geothermal fields and detailed structural geology studies will be discussed.

4.1. Güzelkent geothermal field

The geothermal field in Güzelkent village (Figure 5) consists of five geothermal ponds of various sizes with a fluid temperature between 29 °C and 33 °C (Figure 6). Güzelkent's hot springs are naturally exposed along the Mengel River bed, which is affected by the deformation of the Leylekdağ segment. Leylekdağ segment is an active NW-trending dextral strike-slip fault with minor reverse component (Herece and Akay, 2003; Emre et al., 2013; Gürboğa, 2016). Deep-seated strike-slip fault segments caused deformation in the bend region and formed a local transtension zone so that geothermal fluids could reach the surface via these fault segments. Strike-slip faulting also caused the Mengel River to form a structurally controlled braided-anastomosing drainage along the bend area (Figure 6).

Five geothermal springs (one of the hot springs sampled and labeled as V3) emerge in the intersection area of normal fault segments and strike-slip faults, as well as in the bending area of the Leylekdağ segment. In the north of the hot springs, en échelon normal fault systems within the Yolüstü formation, which were formed under the influence of the dextral strike-slip fault zone, caused a stepped topography (Figure 6). The strikes of these normal faults are approximately N-S and are positioned in accordance with the stresses in the region considering a N-S directional compressive stress ellipsoid. Especially this transtensional deformation and main faults play a very important role in reaching the geothermal fluid to the surface.

NW-trending dextral strike-slip fault sets, which are synthetic with the Leylekdağ segment, are the main controllers. These fault segments have nearly vertical fault planes, striking N30-58°W, and the measured rakes between 0–10°. In addition, during the study, normal and strike-slip fault planes were instead of determined in the Yolüstü formation and in the Varto segment. The strikes

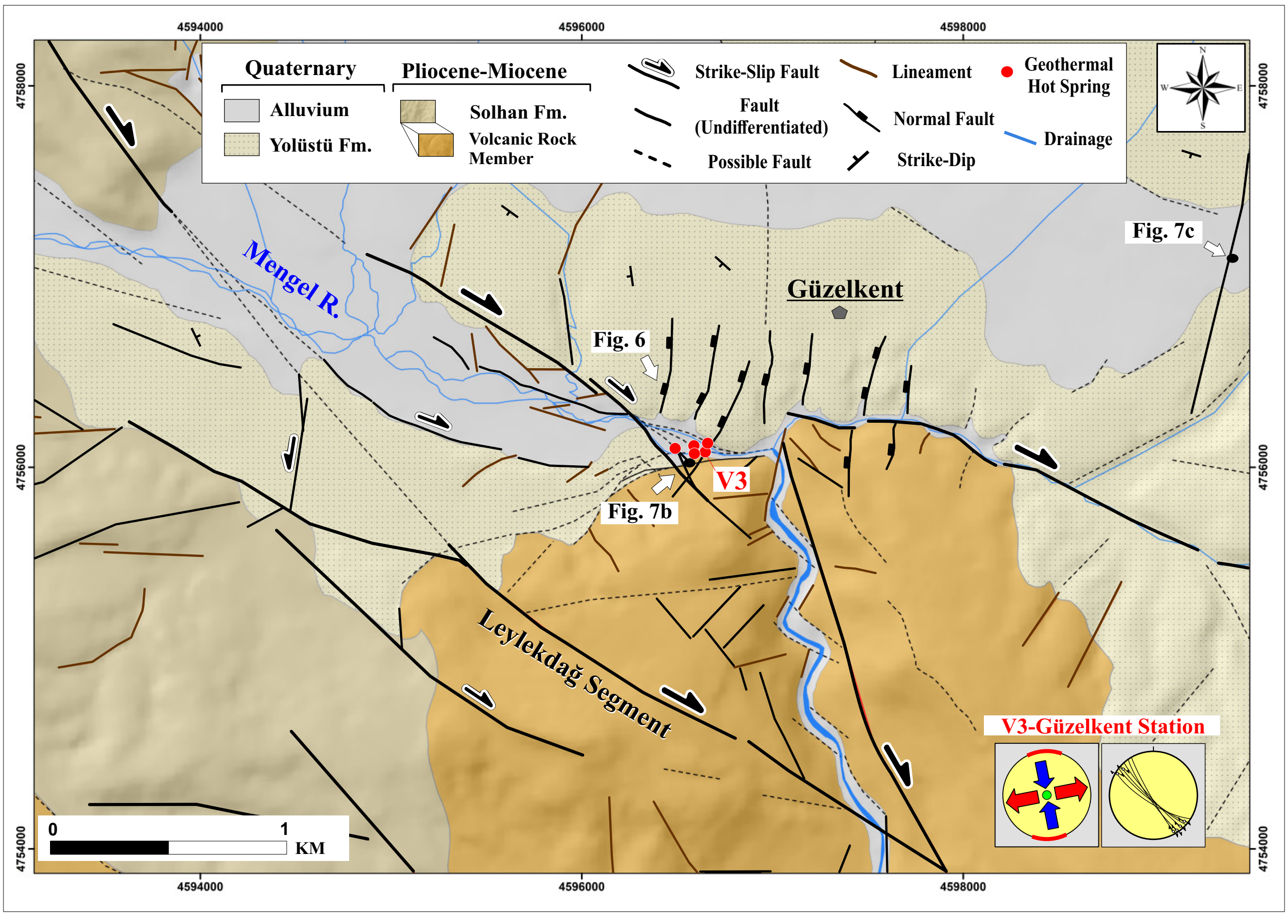

Figure 5. Detailed geological map of the Güzelkent geothermal field (modified after Tarhan, 1991 and Herece and Akay, 2003).

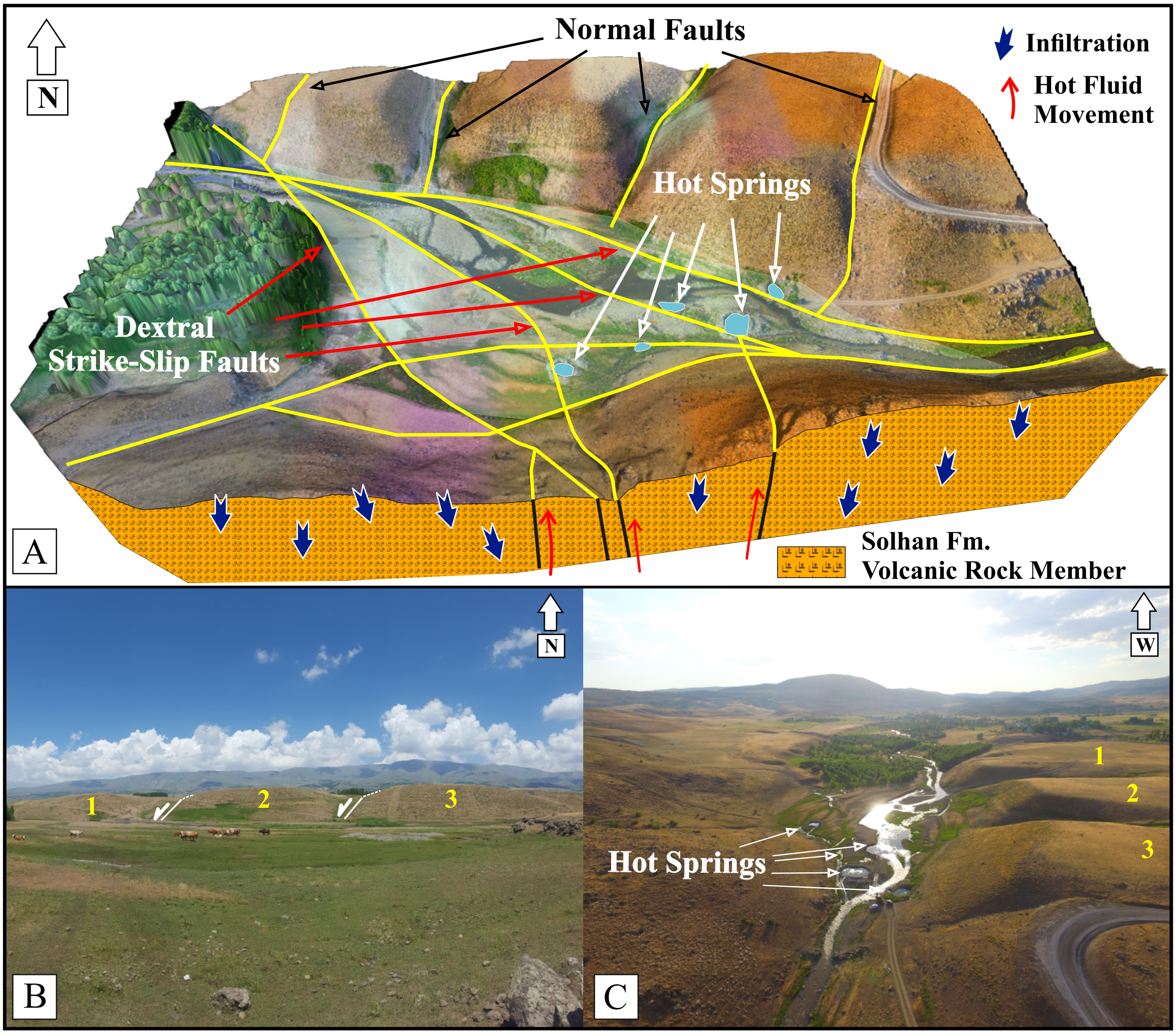

Figure 6. a) Interpretative conceptual 3-D model of the Güzelkent geothermal field (unscaled), b), and c) en échelon normal fault segments.

and dips of these faults are compatible with the fault segments around Güzelkent (Figure 7).

4.2. Alagöztepe geothermal field

Alagöztepe geothermal field is located in the eastern part of the Leylekdağ and Çayçatı segments. The springs are located on a ridge, bounded by the Goşkar River in the south. There are two hot springs visible on the field (Figure 8). The Alagöztepe-I spring, which forms a pond in the terrace sediments has temperatures between 28 °C and 29 °C. The second geothermal source is the Alagöztepe-II spring, which emerged from the southern slope of Alagöztepe ridge. The temperature of this source is relatively higher than the other source and varies between 30 °C and 33 °C.

The region has essential fissure-ridge type travertine formations in terms of geothermal hot springs. These travertines were formed by geothermal fluids reaching the surface via dextral strike-slip faulting with the minor normal component. Travertine layers have slopes in different directions to the south and north of the Alagöztepe ridge with angles between 5° and 35° (Figure 8). The geothermal fluid reaches the surface along the fracture tip on the fissure ridge and the extensional cracks on the travertine slope (Figure 9). The directions of the fractures are compatible with the approximately N-S compressional regime in the region and are the product of a local transtensional movement. All fracture data in the field were subjected to stress tensor evaluation

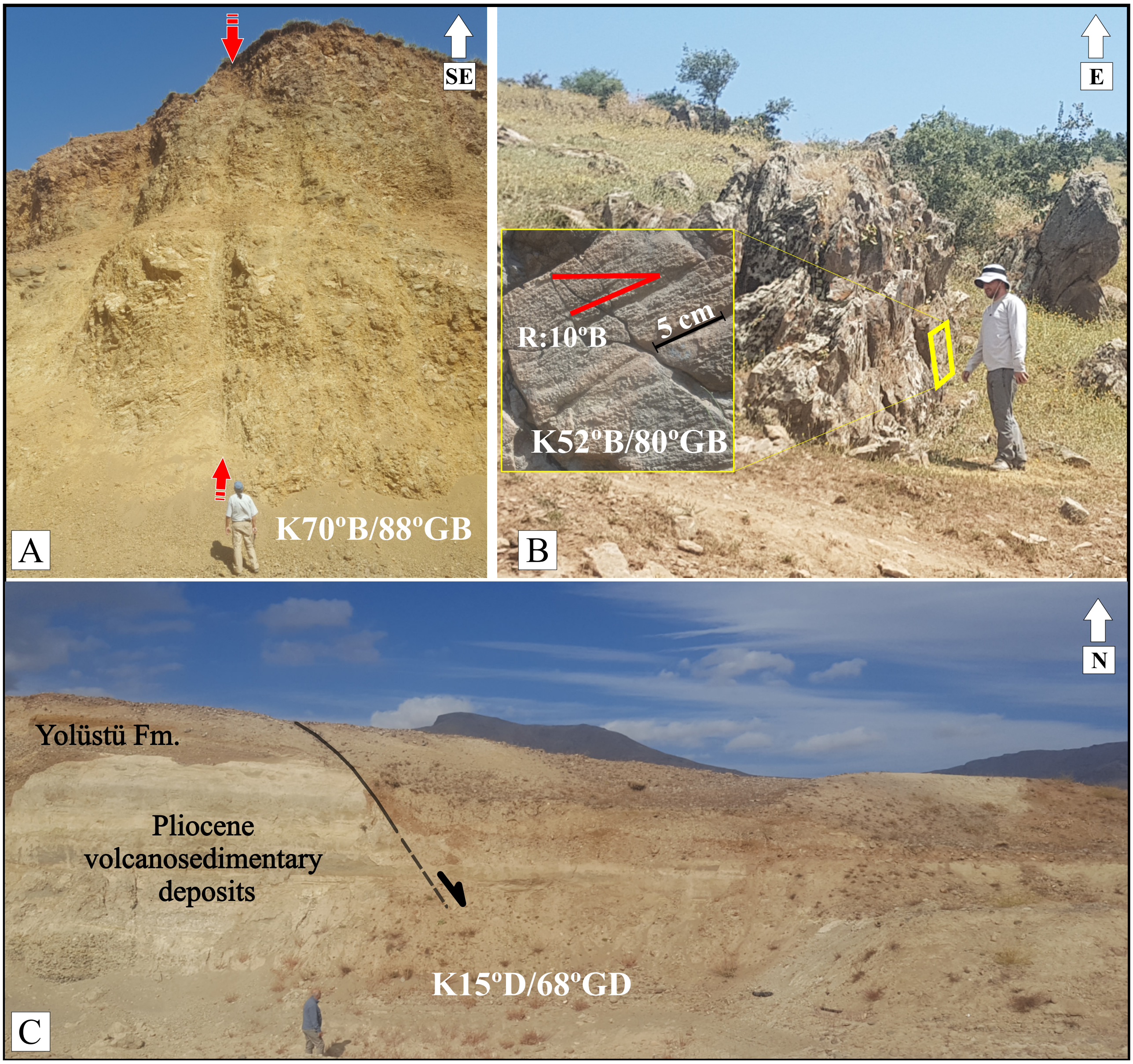

Figure 7. a) Dextral strike-slip fault plane of Varto Segment, b) dextral strike-slip fault plane in Güzelkent geothermal field, and c) normal fault plane within the Yolüstü formation.

within the context of combined kinematic analysis and consequently showed a strike-slip regime character (Figures 8, 9). This result is highly compatible with other stations of this study.

Alluvium deposits of the Goşkar River and Yolüstü formation are important to cover rocks around the geothermal field. Goşkar River flows under the control of fault segments, where the Leylekdağ segment steps over to the south. Smaller NW-trending segments in this area serve as transfer faults in the step-over zone. Fault segments located in the north of the stream are responsible for forming two geothermal springs emerging in the region and the deposition of fissure-ridge travertines and losing their continuity towards the east.

The fault, located to the south of Goşkar River and bound the volcanic rocks of Solhan formation, has significantly changed the topography with the cliff formation. In the southeast of this area, dyke systems parallel to the fault zone were determined (Karaoğlu et al., 2017). The data collected from the field is evidence that rift-controlled magmatism reached the surface with the NW-trending Leylekdağ and Çayçatı segments.

The Abdurrahmanpaşa geothermal spring is also the geothermal source located in the easternmost part of the

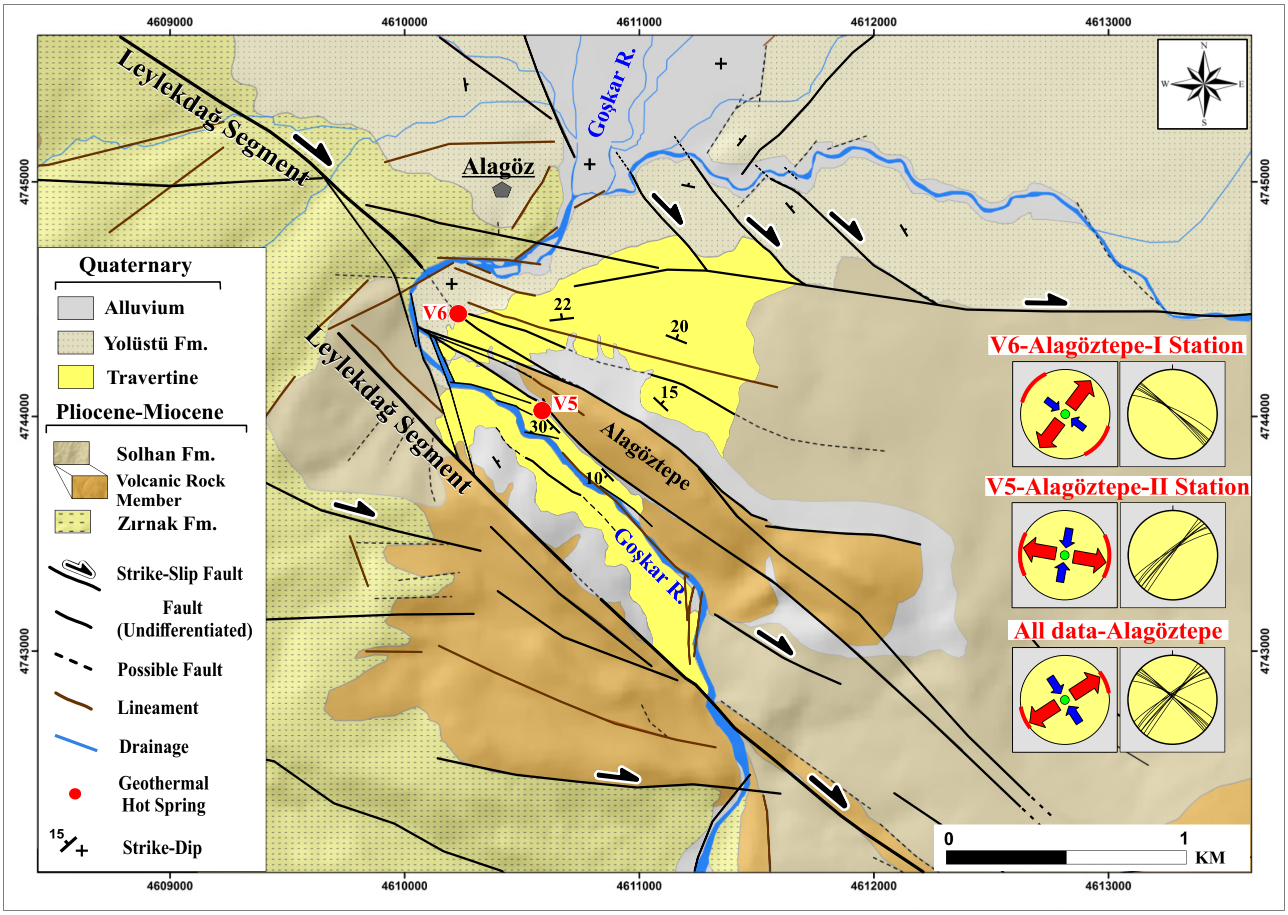

Figure 8. Detailed geological map of the Alagöztepe geothermal field (modified after Tarhan, 1991; Akkuş et al., 2005).

Alagöztepe field (Akkuş et al., 2005). Around the source, there are strike-slip segments with a length of about 5.5 km. These faults, which displace the streams in the right direction, were evaluated as secondary synthetic faults (also called as splay-branch faults; Brace et al., 1966; Cruikshank et al., 1991) separated from the NW-trending main fault segments in the region. In recent years, geothermal fluid outlet is almost nonexistent. It is thought that there is a problem in the surface feeding of the source due to the decreasing precipitation in recent years.

4.3. Kaynarca geothermal field

Kaynarca geothermal field has a hot spring with a temperature of 35 °C, which is located in the stream bed in Kaynarca village (Figure 10). The geothermal source morphologically emerged in the fault intersection area between the Kaynarca and Çayçatı segments.

The dextral strike-slip Kaynarca segment, one of the faults belonging to the Yorgançayır-Kaynarca Fault Zone (YKFZ), is the main structural control in the geothermal field. The approximately NE-trending faults along the Kaynarca River Valley and the antithetic and synthetic faults of the Kaynarca segment intersect along the stream bed, form the geothermal system (Figures 10 and 11). In the south of the hot spring, NW-trending strike-slip faults step over and affected the morphology of Kaynarca River and also formed pull-apart basin (Figure 11a). The faults extending approximately eastward along the valley are synthetic secondary faults separated from the YKFZ segments and offset the Kaynarca River to the rightwards (Figure 11b). Also, it is possible to see transpressional regime structures such as pressure ridges (PR) around the Çayçatı segment (Figure 11c).

During the studies carried out near the Kaynarca geothermal field, faults and lineaments in NE-SW direction were determined in the village of Karameşe, located in the southeast of the Kaynarca segment. Kaynarca mineral water (labeled as V2 in Figure 12) and Karameşe mineral water spring (labeled as V8 in Figure 12) are located on these lineaments and faults. Karameşe mineral spring is the most important natural resource observed on NE-trending sinistral strike-slip fault segments around Varto. It is controlled by a fault segment that is antithetical to the segments of the YKFZ.

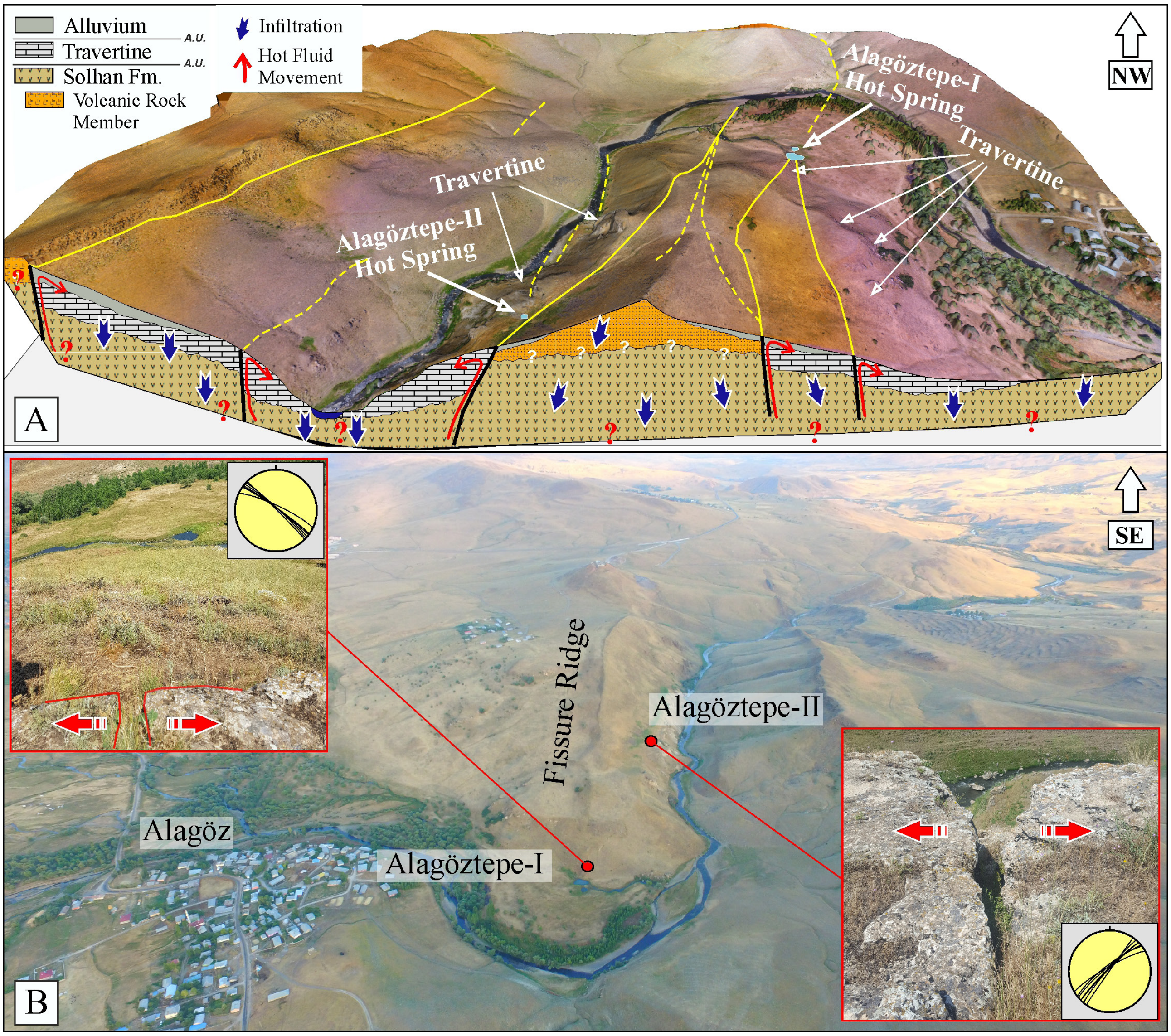

Figure 9. a) Interpretative conceptual 3-D model of the Alagöztepe geothermal field (unscaled), b) aerial view of the Alagöztepe with the extensional crack data.

5. Hydrogeochemistry

Taken together structural controls, lithological properties, and hydrogeochemical analyzes, they provide very important information for geothermal systems (Şener et al., 2017; Uzelli et al., 2017; Şener and Baba, 2019; Baba et al., 2021). As mentioned in hydrogeological studies, there are not many detailed hydrogeochemical studies around Varto. Karaoğlu et al. (2019), the latest and most comprehensive study in the region, evaluated the geothermal fluids around Varto and Karlıova according to their geochemical properties. Karaoğlu et al. (2019) also show that the geothermal fluids are probably heated by steam, and the magma systems under both the Varto caldera and the Özenç volcanoes are the main heat source for the geothermal fluid in the Varto region. The results also reveal that most water in the study area comes from the fractured volcanic rocks in the Varto Region.

In this study, to be able to correlate with geological properties, samples were taken from geothermal springs, mineral waters, and we determine previous cold-water analysis results (Baba et al., 2010) in the study area. The physical and chemical results of the samples are shown in Table.

When the physical properties of the water samples are examined, there are no significant differences between pH values. Temperature values show that geothermal resources are low-medium temperature resources with temperatures between 30 °C and 35 °C. In addition, it is seen that the

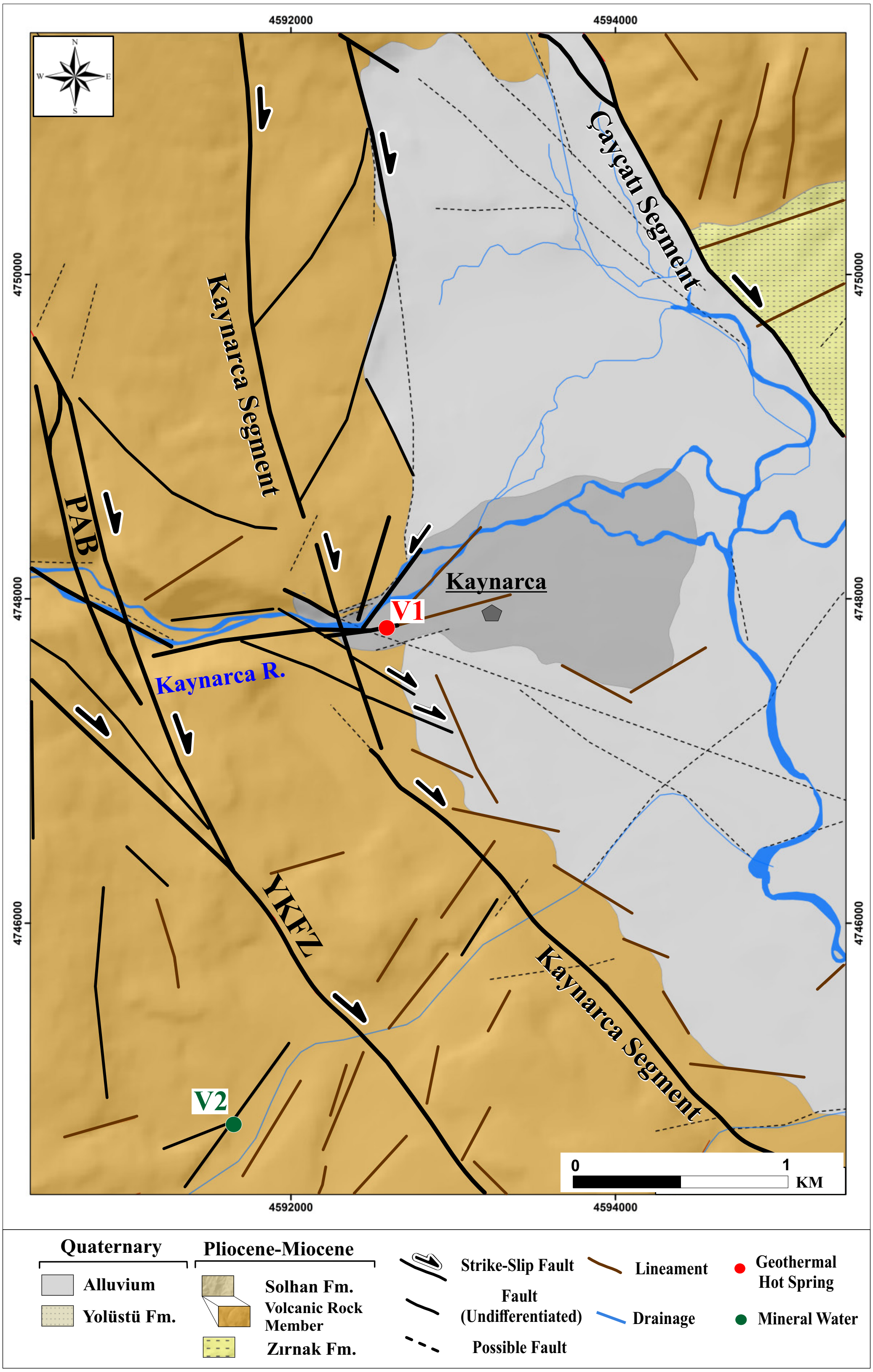

Figure 10. Detailed geological map of the Kaynarca geothermal field (PAB: Pull-apart basin in Figure 11a; modified after Tarhan, 1991; Herece and Akay, 2003).

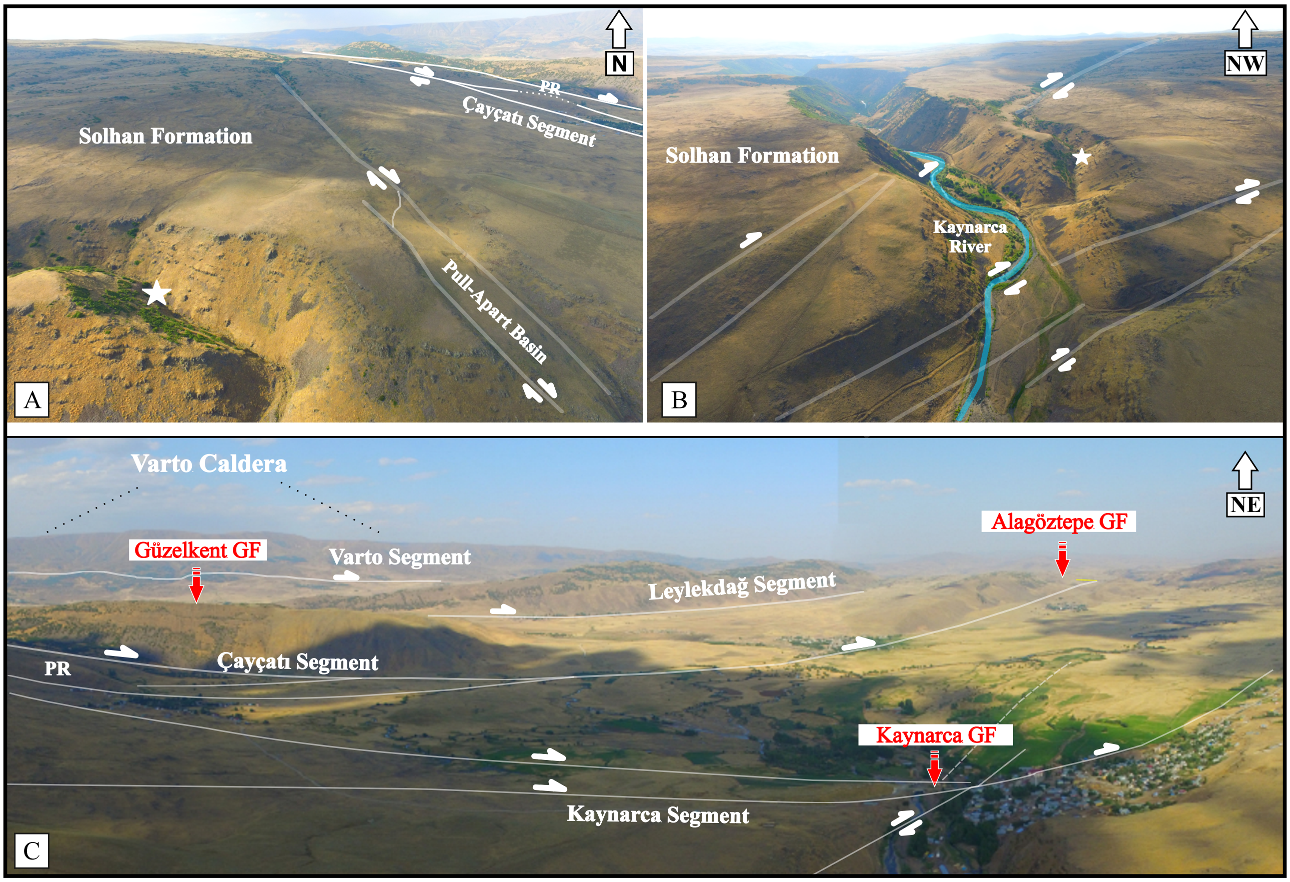

Figure 11. a) Pull-apart basin on YKFZ, b) dextral strike-slip fault segments with river offsets (white-star shows the same location), c) geothermal fields of the Varto region with major fault segments (PR: pressure ridge).

electrical conductivity values are higher in hot springs and mineral waters due to the water-rock interaction that takes place in the deeper groundwater flow processes.

To see the spatial distribution in the study area, the major anion and major cation data of chemical analyzes were also converted into pie diagrams and added to the hydrogeological map (Figure 12). In the Schoeller diagram of the Varto samples, waters with the same origin show similar peaks together (Figure 13). When the table values and pie diagrams are examined, the dissolved ion content of the geothermal fluid, mineral water, and cold water are higher, respectively. Na+K, Cl, and HCO_3 values of geothermal fluids are higher than other groups. In cold waters, while HCO_3 values are high, Cl and Na+K values are lower than other groups. The Karameşe mineral water (V8) sample has high values similar to the geothermal fluids in the region. The reason for higher concentrations and having a high amount of dissolved gas can be explained by deep-seated fault-control, highly permeable pathways, and the residence of the fluid in the carbonate reservoir (Clausser et al., 2002; May, 2002; Berberich et al., 2017). Apart from this, Abdurrahmanpaşa hot spring (V9) having different concentration values than the geothermal fluid can be explained because the source is in the stream bed and is directly mixed with cold water. The flow rate of the current source is too low to be measured and it loses its activity especially in dry periods.

According to the cation distributions of samples in the Piper diagram, the cold waters are of the calcium and mixed type, the geothermal fluids are of the sodium chloride and mixed type, and the mineral waters are of the calcium and sodium chloride type (Figure 13). Anion data show that bicarbonate ion is dominant in all waters (close to chloride type in V5). Higher Na-Cl concentrations reflect deep fluid circulation of geothermal springs and mineral waters, volcanic reservoir and magma chamber connection (Karaoğlu et al., 2019). Cold waters reflect surface water character. In addition, high HCO_3 and low Cl contents show that the cold waters are of meteoric origin, as supported by isotope analysis (Uzelli, 2019; Uzelli et al., 2021).

Hydrogeochemistry studies also show that all waters in the study area are in the immature waters section (Uzelli et al., 2021). This means that the waters are mixed

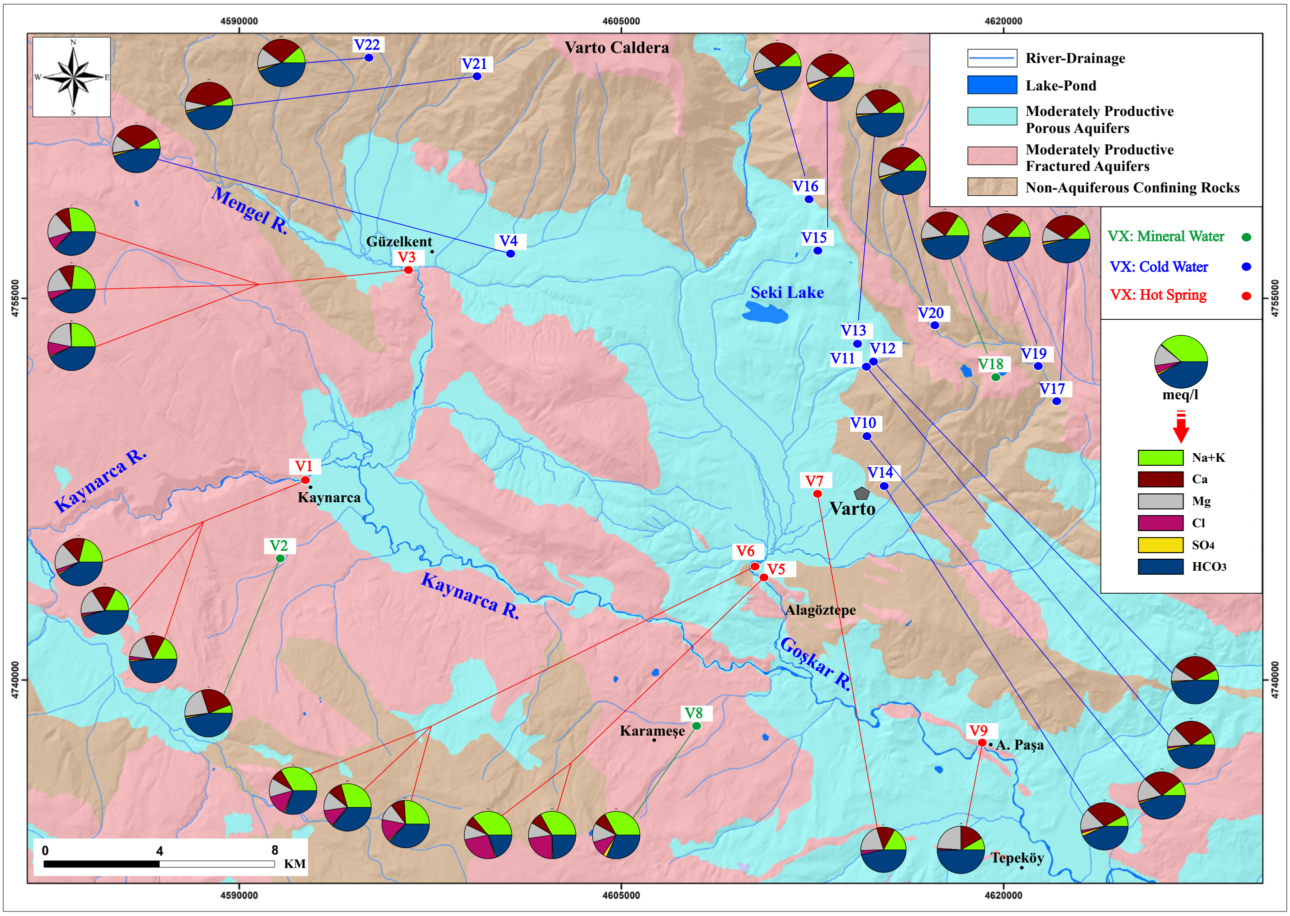

Figure 12. Hydrogeological map of the Varto region with hydrogeochemistry data.

with surface waters, even if they do not reach a partial water-rock balance. For this reason, the results of cation geothermometers cannot determine consistent reservoir temperatures for these waters. Estimated reservoir temperatures of the waters in the study area, according to silica geothermometer calculations, range from 45.7 °C to 156 °C (Uzelli, 2019; Uzelli et al., 2021). It seems more appropriate to use silica geothermometers (quartz, chalcedony, and cristobalite), which give more consistent results below 180 °C (Fournier, 1977).

6. Discussion

Geothermal systems on the Anatolian Plate are predominantly structurally controlled geothermal plays. In Eastern Anatolia, in addition to tectonism, active volcanism processes also affect the geothermal resources (Baba et al., 2010). The study area is located within the VFZ, close to the Karlıova triple junction, in a very important region in terms of tectonics and volcanism.

The VFZ is located in the East Anatolian Contractional Province, where the compressional regime and related deformation are dominant. However, we can see the effect of compressional and extensional tectonics together within the dextral strike-slip VFZ. The main reason for this is thought to be due to the periodical changes in the tectonic regimes in the region. In terms of structural geology, we can see this situation in the bending and step-over areas due to the movement of the strike-slip faults. Since it is a strike-slip fault zone, both transpressional and transtensional deformations can be seen in the VFZ. It is possible to see both reverse and normal fault components in a strike-slip fault segment in different locations, as in the example of the Leylekdağ segment in the VFZ.

When the structural controls in the region are evaluated on the deformation ellipsoid, the faults and cracks in geothermal fields are spatially compatible with the stress regime and deformation pattern of the region (Şengör et al., 1985; Figure 14). According to the current observations made in the geothermal fields in Varto, the geothermal fluid can reach the surface more easily in the areas where the transtensional regime occurs. NW-trending dextral fault segments of VFZ, pull-apart basins, N-trending normal fault segments, intensely deformed fault intersection zones, and N-S directed extension

Table. Chemical and physical analysis results of water samples sampled in the field and compiled from previous studies in the area (taken from *Baba et al., 2010; **Akkuş et al., 2005 and this study).

NO	Name	Type	T (°C)	pH value	EC (µS/cm)	Cl (mg/L)	SO_4 (mg/L)	Na (mg/L)	K (mg/L)	Mg (mg/L)	Ca (mg/L)	HCO_3 (mg/L)
V1	Kaynarca	Hot Spring	35	7.4	2600	58.62	27.92	253.88	36.32	128.64	177.37	1417.18
V2*	Kaynarca M.S.	Mineral Water	14.8	6.16	751	3.53	9.54	22.13	6.07	50.52	90.75	532.98
V3	Güzelkent	Hot Spring	30	7.2	1911	128.16	13.99	270.53	28.75	102.01	90.24	1049.72
V4*	Güzelkent	Cold Water	9.2	6.93	90	0.63	1.67	3.68	1.36	3.58	16.07	67.78
V5*	Alagöztepe-2	Hot Spring	30	7.3	6070	1256.68	45.94	1048.44	68.44	164.72	177.98	1527.58
V6	Alagöztepe-1	Hot Spring	29	7.3	1941	227.93	17.37	326.77	27.21	69.42	71.39	826.68
V7*	Gümgüm Lake	Hot Spring	22.5	6.19	2845	77.31	0.86	269.07	25.78	182.74	189.52	2069.68
V8	Karameşe	Mineral Water	24	7.2	4280	367.84	115.02	704.55	33.38	150.49	173.03	1848.03
V9**	Abdurrahmanpasa	Hot Spring	25	7.5	-	8.5	7	39.9	6.3	66.9	77.8	697
V10*	Varto	Cold Water	11	6.5	136	0.75	1.5	5.66	1.89	5.57	15.72	77.02
V11*	Varto	Cold Water	10.3	6.54	115	1.06	2	4.12	2.3	4.47	14.87	73.94
V12*	Varto	Cold Water	7.2	6.68	60	0.28	0.83	2.68	1.23	2.47	13.22	58.6
V13*	Varto	Cold Water	9.2	6.73	105	0.53	1.49	4.08	1.29	4.38	13.28	70.92
V14*	Varto	Cold Water	11.6	6.22	187	2.55	4.4	6.34	2.44	7.82	25.03	110.91
V15*	Varto	Cold Water	6.7	7.09	63	0.51	2.03	2.63	1.55	2.41	8.45	36.91
V16*	Varto	Cold Water	4.9	7.34	51	0.23	0.78	2.35	1.06	2.08	7.06	33.83
V17*	Varto	Cold Water	7.5	7.11	87	0.44	1.55	4.78	0.97	2.6	12.69	58.54
V18*	Gümgüm Lake	Mineral Water	13.2	5.41	719	4.05	6.44	52.8	18.58	27.47	84.29	499.09
V19*	Varto	Cold Water	6	7.3	63	0.29	0.85	3.24	1.38	2.08	7.53	36.91
V20*	Varto	Cold Water	5.4	6.42	52	0.29	0.99	2.59	1.34	1.61	8.08	33.89
V21*	Varto	Cold Water	8.9	7.72	77	0.55	1.56	3.85	0.84	2.67	26.49	89.34
V22*	Varto	Cold Water	8.6	7.09	61	0.27	0.86	2.64	1.14	2.1	7.08	33.89

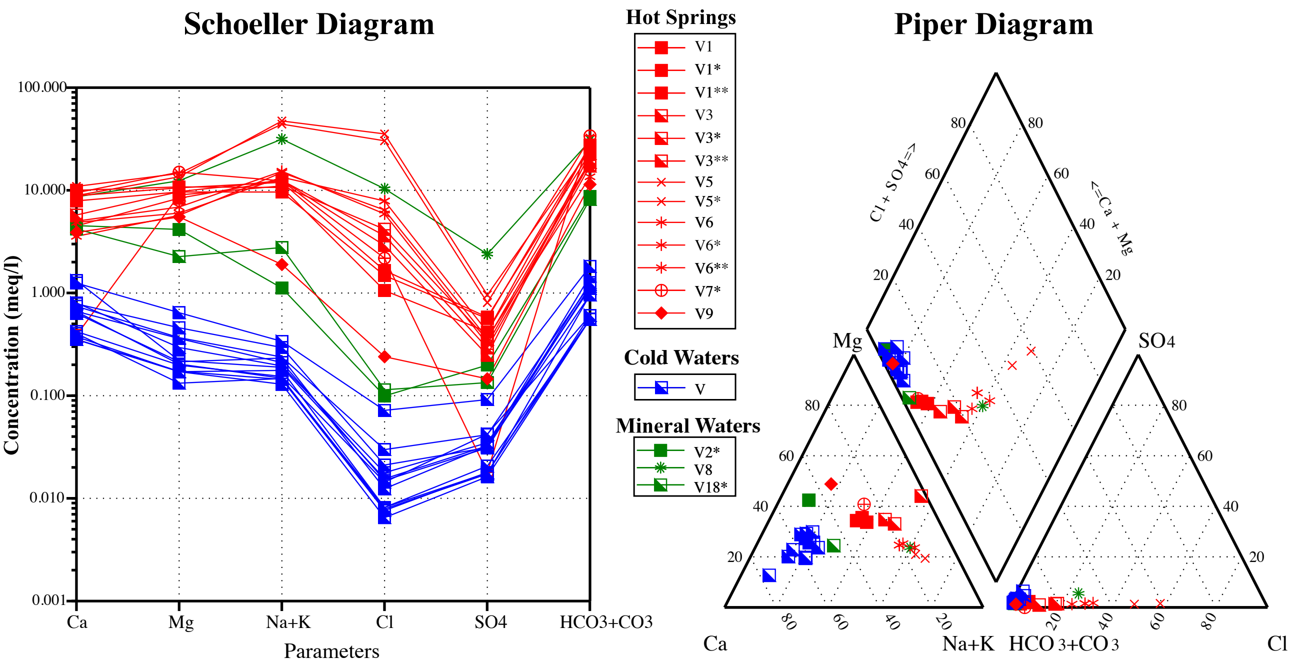

Figure 13. Representation of the waters in the study area in Schoeller (Schoeller, 1962) and Piper diagrams (Piper, 1944).

cracks are the most important structural elements that effect the circulation of geothermal fluid (Figure 14). As the strike of the NW-trending segments shifts to the west, transpressional regime effect increases, and, in this case, reverse fault components begin to be seen in the strike-slip faults as in the Leylekdağ segment (Sançar et al. 2015, 2018; Karaoğlu et al. 2017). In this case, strike-slip fault planes are subject to compression and secondary porosity may decrease. However, this compression may also cause the formation of extension cracks suitable for fluids.

The directions of the fracture systems vary in the range of approximately NW-NE. While the NW-trending fractures are parallel to the fault segments, the N-directed extensional cracks are almost perpendicular to the main segments, and openings are relatively larger. This situation can be explained by the cracks in the N-S direction are affected by greater extensional stress. At the same time, these cracks correspond to tension cracks, which are a natural result of N-S directional compression in the region (Figure 14).

As supported by the geochemical and isotopic data, the cold waters are of meteoric origin and could reach deeper with structural controls, circulating in the depths and exposed to more water-rock interaction (Uzelli, 2019; Uzelli et al., 2021). When the regional distribution of cations and anions in the Varto region was examined, it was determined that the calcium values were higher in the cold water samples, while the sodium and potassium ratios were higher in hot springs. It is thought that the reason for this is that calcium plays a more active role in low temperature and low-pressure weathering conditions in the upper layers of the rocks. The cold-water springs in this area are discharging to the surface via the fault scarps of the VFZ before going to very deep levels. However, towards the south of the study area, the geothermal fluids emerging along the NW-trending instead of extension zones have more rock interaction and move deeper over time and begin to add more sodium to its concentration. As a result, the chemistry of the waters is controlled by ion exchange and hydrolysis reactions (clay degradation of plagioclases, etc.) that take place in underground aquifer environments without atmospheric conditions. The tritium analysis results also support the circulation process in the rocks in Varto in terms of time, together with the elevation relationship (Uzelli, 2019; Uzelli et al., 2021).

The geothermal springs located in the Varto region, where the surface temperatures of springs are range from 20° to 35 °C. In addition, geochemical geothermometer results show that the reservoir temperature of the region reaches up to 156 °C. The local people do not use the resources for direct use applications; hot springs are used for animal husbandry and bathing with primitive spa applications. However, as a result of this study and related studies (Dölek et al., 2018; Uzelli, 2019; Uzelli et al., 2021), in 2020 a new well was drilled in Alagöztepe by the Mineral Research and Exploration Institute, approximately 40 °C fluid was obtained at 830 m with a flow rate of approximately 40–45 L/s. This is proof that there is an important geothermal resource potential in the region.

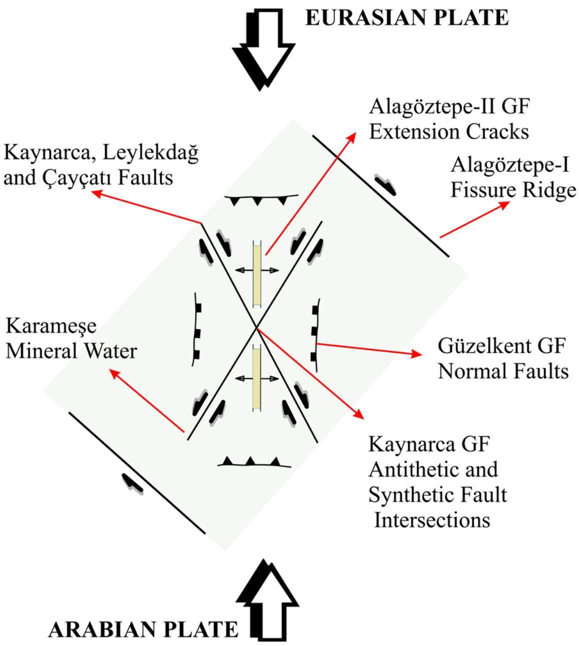

Figure 14. Representation of the structural elements in the Varto fault zone on the deformation ellipsoid (modified after Şengör et al., 1985).

In addition, from a hydrological point of view, the Varto region is very rich in terms of water resources and mineral waters. All hot and cold resources of the region should be protected in a planned and controlled manner and utilized efficiently and sustainably.

In the light of the available data and evaluating the current situation in the region, it is possible to make some practical and economical applications in the short term. For example, in the region where the winter months are long, and the temperature values fall below zero, snowfalls cause many problems, especially transportation problems. Even with the current surface temperature, it may be possible to minimize the snow problem with road heating around the source.

7. Conclusion

This study is based on a multidisciplinary study and determination of the field observations from geothermal fields of the Varto region. The VFZ is the primary control mechanism of the geothermal activity around the Varto. Güzelkent, Kaynarca, Alagöztepe hot springs, and Karameşe mineral water are structurally controlled, and nearly all of them are associated with volcanic rocks. While Güzelkent and Alagöztepe geothermal springs formed in transtensional areas where dextral strike-slip fault segments bend and step-over, Kaynarca source is under the control of secondary fault segments that intersect with the dextral strike-slip Kaynarca fault segment. There are also fissure-ridge type travertine formations associated with faults in the Alagöztepe geothermal field. The other important cold water resources in the region are lakes, mineral water springs, cold water springs in the fault scarps around the Varto Caldera.

Hydrogeochemical analysis results show that the cold waters are of the calcium and mixed type, the geothermal fluids are of the sodium chloride and mixed type, and the mineral waters are of the calcium and sodium chloride type. Higher Na-Cl concentrations reflect deep fluid circulation for geothermal fluids and mineral waters via pathways created by faults.

As a result, we emphasize that the planes of strike-slip faults in transtensional areas are more favorable for secondary permeability and enhances the geothermal fluid circulation, and this can be supported by hydrogeochemical data. Taking this study as an example, which demonstrates the relationship between structural controls, hydrogeochemistry, and geothermal activity, new sites with similar favorable conditions in the tectonically active Eastern Anatolia Region should be explored.

Acknowledgments

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References

Akay E, Erkan E, Ünay E (1989). Stratigraphy of the Muş Tertiary Basin. Bulletin of the Mineral Research and Exploration 109: 59-76.

Akay E, Göncüoğlu MC, Turan N (1988). 1/100.000 Scaled Geological Maps of Turkey with Distortion, Muş H33 (K47) Map. Ankara-Turkey: MTA General Directorate.

Akkuş İ, Akıllı H, Ceyhan S, Dilemre A, Tekin Z (2005). Geothermal Resources Inventory of the Turkey. Ankara: MTA General Directorate Inventory Series-201 (in Turkish).

Ambraseys N, Zatopek A (1968). The Varto Ustukran earthquake of 19 August 1966, Bulletin of the Seismological Society of America 58: 47–102.

Baba A, Uzelli T, Sozbilir H. (2021). Distribution of geothermal arsenic in relation to geothermal play types: A global review and case study from the Anatolian plate (Turkey). Journal of Hazardous Materials 2021 Jul 414: 125510. doi: 10.1016/j.jhazmat.2021.125510.

Baba A, Yiğitbaş E, Ertekin C (2010). Hydrogeochemistry of Geothermal Resources of Eastern Part of Turkey: A Case Study, Varto Region. In: World Geothermal Congress 2010; 25-29 April 2010, Bali, Indonesia. pp. 1-8.

Barka AA (1992). The North Anatolian fault zone. Annales Tectonicae 6 (Suppl.): 164-195.

Berberich G, Berberich M, Ellison A (2017). Fluctuations of gas concentrations in three mineral springs of the East Eifel Volcanic field (EEVF). arXiv: Geophysics.

Bozkurt E (2001). Neotectonics of Turkey - a synthesis. Geodinamica Acta 14: 3-30.

Brace WF, Paulding BW, Scholz CH (1966). Dilatancy in the fracture of crystalline rocks. Journal of Geophysical Research 71: 3939-3942.

Buket E, Temel A (1998). Major-element, trace-element, and Sr-Nd isotopic geochemistry and genesis of Varto (Muş) volcanic rocks, Eastern Turkey. Journal of Volcanology and Geothermal Research 85: 405–422.

Clauser C, Griesshaber E, Neugebauer HJ (2002). Decoupled thermal and mantle helium anomalies: Implications for the transport regime in continental rift zones. Journal of Geophysical Research 107: B11, 2269. doi:10.1029/2001JB000675.

Cruikshank KM, Zhao G, Johnson AM (1991). Analysis of minor fractures associated with joints and faulted joints. Journal of Structural Geology 13: 865-886.

Çağlayan MA, İnal RN, Şengün M, Yurtsever A (1983). Structural setting of Bitlis Massif. In: Tekeli O and Göncüoğlu C (Editors), Geology of the Taurus belt. International Symposium. pp. 245-254.

Delvaux D, Sperner B (2003). Stress tensor inversion from fault kinematic indicators and focal mechanism data: the TENSOR program. In: New Insights into Structural Interpretation and Modelling (D. Nieuwland, Editor). Geological Society, London: Special Publications 212, pp. 75-100.

Demirtaşlı E, Pisoni C (1965). Geology of Ahlat-Adilcevaz region (north of Lake Van). MTA Journal 64: 22-36 (in Turkish).

Dewey JF, Hempton MRS, Kidd WSF, Saroğlu F, Şengör AMC (1986). Shortening of continental lithosphere, the neotectonics of Eastern Anatolia, a young collision zone. In: Coward, M.P., Ries, A.C. (Editors.). Collision Zone Tectonics, Geological Society of London Special Publication 19, pp. 3– 36.

Dölek İ, Baba A, Sözbilir H, Şener MF, Uzelli T (2018). Characterization of Geothermal Resources in Muş Province, Determination of Potential and Usage Areas Project Report. Muş Alparslan University. BAP-17.EMF-4914-01; 13/09/2017-13/05/2018) (in Turkish).

Emre Ö, Duman TY, Özalp S, Elmacı H, Olgun Ş et al. (2013). Active Fault Map of Turkey with an Explanatory Text, 1:1.250.000 scale. Ankara-Turkey: General Directorate of Mineral Research and Exploration, Special Publication Series-30.

Faulds JE, Coolbaugh MF, Benoit D, Oppliger G, Perkins M et al. (2010b). Structural controls of geothermal activity in the northern Hot Springs Mountains, western Nevada, The tale of three geothermal systems (Brady's, Desert Perk, and Desert Queen). Geothermal Resources Council Transactions 34: 675-683.

Faulds JE, Coolbaugh M, Bouchot V, Moeck I, Oguz K (2010a). Characterizing structural controls of geothermal reservoirs in the Basin and Range, USA, and western Turkey, Developing successful exploration strategies in extended terranes. In: World Geothermal Congress; Bali, Indonesia, 25-30 April 2010. pp. 11.

Faulds JE, Hinz NH (2015). Favorable tectonic and structural settings of geothermal systems in the Great Basin region, western USA, Proxies for discovering blind geothermal systems. In: World Geothermal Congress; Melbourne, Australia, 19-25 April 2015. pp. 6.

Faulds JE, Hinz NH, Coolbaugh MF, Cashman PH, Kratt C et al. (2011). Assessment of favorable structural settings of geothermal systems in the Great Basin, Western USA. Geothermal Resources Council Transactions 35: 777-783.

Fournier RO (1977). Chemical geothermometers and mixing models for geothermal systems. Geothermics 5: 41-50.

Göncüoğlu MC, Turhan N (1983). Geology of the Bitlis metamorphic belt. In: Tekeli, O. and Göncüoğlu, C. (Editors). Geology of the Taurus belt. International Symposium, pp. 237-244.

Göncüoğlu MC, Turhan N (1985). General geology of the middle part of the Bitlis metamorphic belt. Ankara: General Directorate of Mineral Research and Exploration Report-7707 (in Turkish).

Gürboğa Ş (2016). The termination of the North anatolian fault system (NAFS) in Eastern Turkey. International Geology Review 58 (12): 1557–1567.

Herece E (2008). Geological Map of the EAF, Göynük Segment. Ankara: Mineral Research and Exploration Institute (in Turkish).

Herece A, Akay E (2003). Atlas of North Anatolian Fault (NAF). Ankara: General Directorate of Mineral Research and Exploration: Special Publication Series-2.

Hubert-Ferrari A, King G, Woerd JVD, Villa I, Altunel E et al. (2009). Long-term evolution of the North Anatolian fault: New constraints from its eastern termination. Geological Society London Special Publications 311-1: 133–154.

İlker S (1966). Report on the 1:25000 scale oil survey of Karaköse-J48 a4, d1 plots in Erzurum-Muş region. Ankara: MTA Reports-4177 (in Turkish).

Karaoğlu, Ö (2020). Varto Caldera (Bingöl, Eastern Anatolia) Explosive Eruption Products and Caldera Formation, Afyon Kocatepe University Journal of Sciences and Engineering 20: 528-542. doi: 10.35414/akufemubid.695256

Karaoğlu Ö, Selçuk AS, Gudmundsson A (2017). Tectonic controls on the Karliova triple junction (Turkey): Implications for tectonic inversion and the initiation of volcanism. Tectonophysics 694: 368–384.

Karaoğlu Ö, Bayer Ö, Turgay MB, Browning J (2020b). Thermomechanical interactions between crustal magma chambers in complex tectonic environments: Insights from Eastern Turkey. Tectonophysics 793.

Karaoğlu Ö, Bazargan M, Baba A, Browning J (2019). Thermal fluid circulation around the Karliova triple junction: Geochemical features and volcano-tectonic implications (Eastern Turkey). Geothermics 81: 168-184.

Karaoğlu Ö, Browning J, Salah MK, Elshaafi A, Gudmundsson A (2018). Depth of magma chambers at three volcanic provinces in the Karlıova region of Eastern Turkey. Bulletin of Volcanology 80: 69. doi: 10.1007/s00445-018-1245-x

Karaoğlu Ö, Gulmez F, Gocrnengil G, Lustrino M, Di Giuseppe P et al. (2020a). Petrological evolution of Karliova-Varto volcanism (Eastern Turkey): Magma genesis in a transtensional triple-junction tectonic setting. Lithos 364.

Ketin İ (1969). About the North Anatolian Fault. Journal of Mineral Research and Exploration 72: 1–27 (in Turkish).

Ketin İ (1976). A comparison between the San Andreas and North Anatolian Faults. Bulletin of the Turkish Geological Institute 19: 149–154 (in Turkish).

May F (2002). Säuerlinge der Vulkaneifel und der Südeifel. Mainzer Geowissenschaftliche Mitteilungen Mainz 31: 7–57 (in German).

McKenzie D (1972). Active tectonics of the Mediterranean region. Geophysical Journal of the Royal Astronomical Society 30: 109–185.

Moeck IS, Beardsmore G (2014). A new 'geothermal play type' catalog: Streamlining exploration decision making. In: 39th Workshop on Geothermal Reservoir Engineering; Stanford University, Stanford, CA.

Notsu K, Fujitani T, Ui T, Matsuda J, Ercan T (1995). Geochemical features of collision-related volcanic rocks in central and eastern Anatolia, Turkey. Journal of Volcanology and Geothermal Research 64: 171–192.

Okay AI, Tüysüz O (1999). Tethyan sutures of northern Turkey. Geological Society, London, Special Publications 156: 475–515.

Pearce JA, Bender JF, De Long SE, Kidd WSF, Low PJ et al. (1990). Genesis of collision volcanism in Eastern Anatolia, Turkey. Journal of Volcanology and Geothermal Research 44: 189–229.

Perinçek, D (1980). Volcanic Triassic in Bitlis metamorphics. Geology Bulletin of Turkey 23/2: 201-211 (in Turkish).

Perinçek D, Özkaya I (1981), Arabian plate northern margin tectonic evolution. Yerbilimleri 8: 91-101 (in Turkish).

Piper AM (1944). A graphical procedure in the geochemical interpretation of water analyses. Eos Transactions American Geophysical Union: 914-923.

Sançar T, Akyüz HS, Schreurs G, Zabcı C (2018). Mechanics of plio-quaternary faulting around the Karliova triple junction: implications for the deformation of Eastern part of the Anatolian Scholle. Geodinamica Acta 30-1: 287-305.

Sançar T, Zabcı C, Akyüz HS, Sunal G, Villa IM (2015). Distributed transpressive continental deformation: The Varto Fault Zone, eastern Turkey. Tectonophysics 661: 99-111.

Schoeller H (1962). Leseaux Souterraines. Mason Et Cie: Paris. pp. 642.

Siler DL, Faulds JE, Hinz NH (2015). Regional and Local Geothermal Potential Evaluation: Examples from the Great Basin, USA, Iceland and East Africa. In: World Geothermal Congress 2015; Melbourne, Australia, 19-25 April 2015.

Sözeri TE (2007). Investigation of Facies and Reservoir Properties of Burdigalian Limestones Around Muş (Eastern Anatolia). Master Thesis, Ankara University Graduate School of Natural and Applied Sciences, Ankara, Turkey (in Turkish).

Şaroğlu F (1988). Age and offset of the North Anatolian Fault. In: 1987 Melih Tokay symposium; Ankara, Special Publication Middle East Technical University. pp. 65–79.

Şaroğlu F, Yılmaz Y (1986). Geological Evolution and Basin Models in the Neotectonic Period in Eastern Anatolia. MTA Journal 107: 73-94 (in Turkish).

Şener MF, Baba A (2019). Geochemical and hydrogeochemical characteristics and evolution of Kozaklı geothermal fluids, Central Anatolia, Turkey. Geothermics 80: 69-77.

Şener MF, Şener M, Uysal IT (2017). The evolution of the Cappadocia Geothermal Province, Anatolia (Turkey): geochemical and geochronological evidence. Hydrogeology Journal 25 (8): 2323-2345.

Şengör AMC (1979). The North Anatolian transform fault: its age, offset and tectonic significance. Journal of the Geological Society of London 136 (3): 269–282.

Şengör AMC, Görür N, Şaroğlu F (1985). Strike slip faulting and related basin formations in zones of tectonic escape: Turkey as a case study. In: K. T. Biddle & N. Christie- Blick (editors). Strike-slip faulting and basin formation, society of economic paleontologists and mineralogists, Tulsa, Oklahoma: Special Publication 37, pp. 227– 264.

Tan O, Tapırdamaz MC, Yörük A (2008). The earthquake catalogues for Turkey. Turkish Journal of Earth Sciences 17 (2): 405–418.

Tarhan N (1991). Geology and petrology of Neogene volcanics around Hınıs-Varto-Karlıova (Erzurum-Muş-Bingöl). MTA Journal 113: 45-60 (in Turkish).

Tarhan N (1997). 1/100000 Scaled Geological Maps of Turkey, Erzurum J45 and J 46 Sheets. General Directorate of Mineral Research and Exploration Institute. Ankara-Turkey: Department of Geological Studies (in Turkish).

Uzelli T (2019). Structural Controls of Geothermal Systems in Varto and Muş Basins (Eastern Anatolia, Turkey). PhD, Hacettepe University, Graduate School of Science and Engineering, Department of Geological Engineering, Ankara, Turkey, pp. 193 (in Turkish).

Uzelli T, Baba A, Mungan GG, Dirik K, Sözbilir H (2017). Conceptual model of the Gülbahçe geothermal system, Western Anatolia, Turkey: Based on structural and hydrogeochemical data. Geothermics 68: 67–85.

Uzelli T, Baba A, Sozbilir H., Sener MF, Dolek I et al. (2021). Structural Controls on Geothermal Activity in the East Anatolian Contractional Province-Turkey: Case Study: Muş and Varto Basins. In: World Geothermal Congress 2020+1; Reykjavik, Iceland, April -October 2021.

Wallace RE (1968). Earthquake of August 19, 1966. Varto Area, Eastern Turkey. Bulletin of the Seismological Society of America 58: 11–45.

Yılmaz Y, Güner Y, Şaroğlu F (1998). Geology of the Quaternary volcanic centers of the East Anatolia. Journal of Volcanology and Geothermal Research 85: 173-210.

Yılmaz Y, Saroğlu F, Güner Y (1987). Initiation of the neomagmatism in East Anatolia. Tectonophysics 134: 177–199.