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Geothermal Potential of the Triple Junction Area in Eastern Anatolia (Türkiye)

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1 INTRODUCTION

Eastern Anatolia is a tectonically dynamic region where geothermal resources are strongly influenced by major fault zones and volcanic activity. Although the area is widely recognized for its seismic and volcanic hazards, its geothermal potential remains underexplored compared to western Türkiye. The Karlıova Triple Junction (KTJ) offers a structurally favorable setting for geothermal systems due to the interaction of the North Anatolian Fault Zone (NAFZ), East Anatolian Fault Zone (EAFZ), and Varto Fault Zone (VFZ), which create deformation zones, pull-apart basins, and increased crustal permeability. This study is significant because IGNIS recognizes the potential for high-enthalpy geothermal systems in a region where resources have not yet been fully evaluated. By developing a structural and thermal framework using multidisciplinary data – including geological mapping, drone-based remote sensing, hydrogeochemical sampling, and geophysical analysis – this work provides important scientific input for future geothermal exploration and sustainable utilization in Türkiye's eastern provinces. The findings advance regional understanding of fault-controlled fluid circulation and crustal-scale heat transfer processes in the KTJ.

2 STRUCTURAL AND VOLCANIC FRAMEWORK

The KTJ is one of the most tectonically active regions in Türkiye, where the NAFZ, EAFZ, VFZ and Bitlis–Zagros Suture Zone (BZSZ) converge (Şengör et al., 1988; Bozkurt, 2001; Reilinger et al., 2006). This junction accommodates the westward extrusion of the Anatolian Plate, resulting from the ongoing collision between the Arabian and Eurasian plates, and generates a highly partitioned strain field characterized by dextral motion along the NAFZ and sinistral displacement along the EAFZ (Şengör et al., 1988; Koçyiğit et al., 2001). The interaction of these major strike-slip systems produces intense faulting, seismic activity, and widespread fracturing, which enhances crustal permeability. This dynamic tectonic environment has also controlled the evolution of Quaternary volcanism across the Solhan–Muş–Bingöl–Ağrı region. The Karlıova–Varto volcanic field, consisting mainly of basaltic to andesitic lavas, is one of the youngest volcanic provinces in Türkiye and is attributed to lithospheric thinning, asthenospheric upwelling, and transtensional deformation associated with strike-slip fault interaction (Keskin, 2003; Yılmaz et al., 1998; Şengör et al., 1988). The combination of high heat flow, magmatic activity, and fault-controlled permeability zones provides favorable conditions for geothermal fluid circulation around the KTJ (Figure 1).

To define geothermal systems in such settings, it is essential to characterize structural controls, stratigraphy and lithology. Areas with elevated geothermal gradients due to magmatism, as well as fault intersections, step-overs, transfer zones, and pull-apart basins, are considered the most suitable structural environments for geothermal resources (Faulds et al., 2010; 2011; Moeck, 2014; Faulds and Hinz, 2015; Uzelli et al., 2021). This relationship is especially evident in Eastern Anatolia, where geothermal manifestations such as hot springs are strongly controlled by faults. The VFZ, located east of the KTJ, plays a key role in regional deformation and likely contributed to the initiation of volcanism with shallow magma chambers as a continuation of the NAFZ (Karaoğlu et al., 2016; 2017; 2019; Ketin, 1948; Emre et al., 2018;). The historical earthquake sequence demonstrates repeated ruptures, leaving seismic gaps on critical segments such as the Yedisu segment near the study area. Paleoseismic data indicate a recurrence interval of 245 ± 55 years, suggesting a significant seismic hazard (Akyüz et al., 2009). Earthquake catalogs from Boğaziçi University Kandilli Observatory show that most epicenters occur at depths less than 10 km, with magnitudes reaching Mw 6.4, further emphasizing the active and hazardous nature of the region.

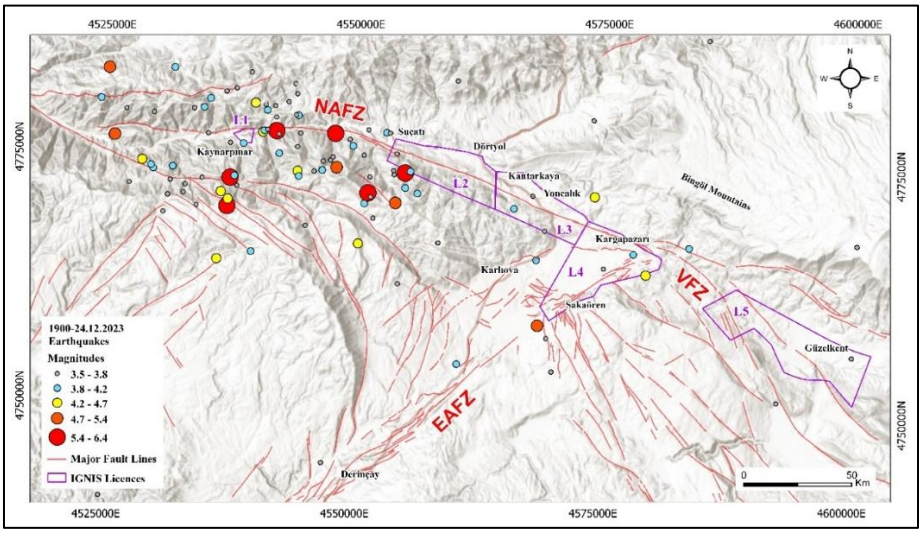


Figure 1. Structural map of the Karlıova Triple Junction (KTJ) region showing major fault zones, earthquake epicenters (M3.5–5.4) recorded between 1900–2023, and the IGNIS Energy geothermal license areas (L1–L5, faults taken from Emre et al., 2018).

3 METHODS AND EXPLORATION ACTIVITIES

This study employs a multidisciplinary approach to assess the structural controls, subsurface thermal regime, and hydrogeochemical characteristics of the geothermal system associated with the Karlıova Triple Junction. Geological and hydrogeological maps were updated through systematic field surveys focused on lithological boundaries, fault mapping, morphological indicators, and geothermal surface manifestations, including travertine deposits, fumaroles, and altered zones. Structural data, such as fault orientations, fracture density, and kinematic indicators, were recorded across the license areas to evaluate deformation patterns and their influence on reservoir permeability. Remote sensing techniques supported detailed structural interpretation. High-resolution drone photogrammetry campaigns produced orthophotos, digital surface models (DSMs), and digital elevation models (DEMs). Images were processed using point-cloud reconstruction and georeferenced under the WGS-84 UTM system, achieving a ground sampling distance of 4.5–13.6 cm. Lineament mapping was performed manually using DEM-derived topography and orthomosaic imagery within a GIS environment. All spatial layers were compiled into an integrated geodatabase.

Hydrogeochemical analyses of thermal springs determined the concentrations of major cations and anions and identified water–rock interaction processes. In situ measurements included temperature, pH, and electrical conductivity using an HQ40d device. Stable isotope compositions of $\delta^{18}O$ and δD were analyzed to distinguish fluid origin and circulation depth. These geochemical datasets were complemented by literature findings for regional comparison and contextual interpretation. Geophysical constraints were incorporated to better delineate reservoir geometry and key structural controls. Three-dimensional MT inversion models were integrated with geological observations to identify conductive zones interpreted as cap rock units above deeper high-resistivity reservoirs. By combining field-based structural mapping, isotopic signatures, and geophysical anomalies, a conceptual geothermal system model was developed to describe fault-controlled deep fluid circulation and to identify priority drilling targets for future exploration.

4 RESULTS AND DISCUSSION

The objective of this study is to determine the geochemical, mineralogical, and thermal characteristics of the subsurface formations and to evaluate their potential contribution to geothermal fluid flow and reservoir development.

4.1 Water Chemistry

Before this study, preliminary geochemical assessments of thermal and cold-water sources in the region were conducted using available chemical analyses from the literature (e.g., Akkuş et al., 2005; Baba et al, 2010) and field-based consultations. Major ion data were evaluated with Piper and Schoeller diagrams to identify water types and fluid–rock interaction characteristics. The results indicate multiple hydrochemical facies across the region, with waters dominated by sodium–chloride and sodium–bicarbonate types, especially in the Kaynarpınar area, due to interaction with volcanic and carbonate lithologies. Mixed-type waters observed in some springs and wells (e.g., Bingöl-Kos, Hacılar, Sabırtaşı) indicate the influence of meteoric water mixing, particularly from surface discharge along the Perisuyu Riverbed. Spatial variation in cation and anion concentrations highlights

the impact of both shallow and deep fluid circulation pathways. However, since these datasets are limited and compiled from different time periods, detailed major ion, trace element, and stable isotope ($\delta^{18}O$–δD) analyses are still required to better resolve groundwater–geothermal fluid relationships, quantify reservoir contributions, and assess reservoir temperature using geothermometers in the next phases of the project. The Piper diagram (Figure 2) shows that hot waters predominantly plot within Na–Cl and Na–HCO_3 facies, reflecting deep fluid circulation and water–rock interaction with volcanic and carbonate lithologies. Cold waters fall toward the Ca–Mg–HCO_3 field, representing shallow meteoric inputs. The Schoeller diagram supports this distinction, with geothermal wells showing enriched Na^+, K^+, and Cl^-, while cold waters exhibit significantly lower ionic concentrations. The convergence trend between cold and some thermal waters suggests mixing processes, particularly where springs discharge near the Perisuyu Riverbed.

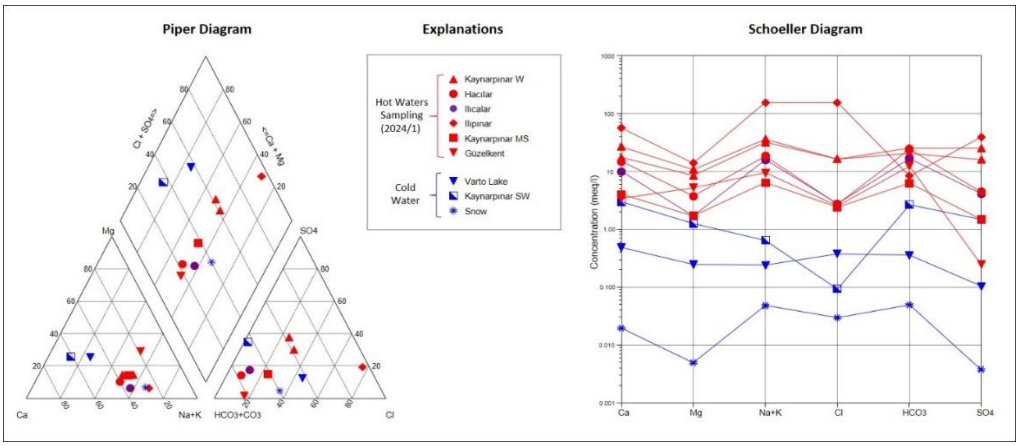


Figure 2. Piper and Schoeller diagrams of sampled waters in and around the study area.

Most geothermal samples fall within the immature to partially equilibrated region of the Giggenbach diagram (Figure 3), indicating that the fluids have undergone mixing and incomplete chemical equilibrium during ascent. Their shift toward the Na-rich apex reflects the influence of a high-temperature reservoir, although mixing with cooler waters obscures their full geothermometric maturity. Cold waters cluster at the Mg-rich vertex, confirming shallow groundwater signatures with minimal geothermal contribution. These results highlight the need for updated silica and Na–K–Ca geothermometers to more accurately constrain reservoir temperatures.

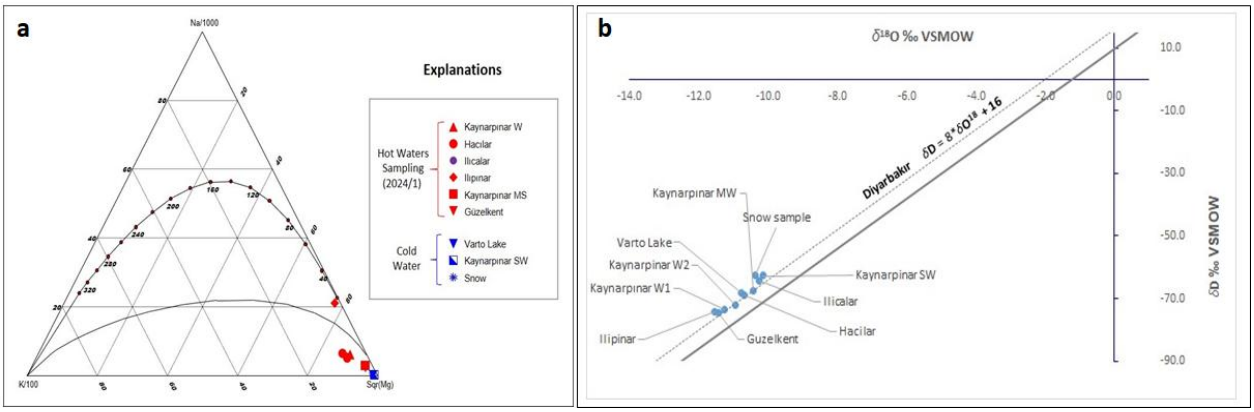


Figure 3. a) Na–K–Mg ternary geothermometer diagram and b) $\delta^{18}O$–δD diagram

In the $\delta^{18}O$–δD diagram, thermal and cold waters cluster near the meteoric line, indicating a meteoric origin for recharge (Figure 4). However, slight $\delta^{18}O$ enrichment in the Kaynarpınar and Ilıpınar samples suggests water–rock interaction at elevated temperatures and possible steam loss or magmatic input. The alignment of snow, lake, and spring waters indicates active recharge relationships. The spreading trend between hot and cold waters further supports the mixing hypothesis, consistent with the major ion results.

4.2 Rock Chemistry

Core samples were collected from various depths of the YDS-1 well (Kaynarpınar) and analyzed using X-ray fluorescence (XRF) and X-ray diffraction (XRD) techniques. XRF analyses indicate that the lithological units are predominantly silica- and alumina-rich, volcanic-derived rocks, exhibiting variable alteration intensities with depth. The major oxide composition shows distinct geochemical zoning: SiO_2 contents exceed 55% at depths of

200 m and 550 m, while Al_2O_3 reaches up to 35% and FeO exceeds 22% around 200 m, indicating a strongly altered interval with possible hydrothermal influence. Na_2O levels remain above 2% in the 50–550 m range, suggesting mobilization of alkali elements through fluid–rock interaction. XRD analyses confirm the presence of dolomite, kaolinite, quartz, and ankerite, with dolomite consistently identified across all sampled intervals. The widespread occurrence of dolomite and kaolinite reflects hydrothermal alteration under moderate to high temperature conditions, while quartz and ankerite indicate silicification and carbonate replacement processes. These mineral assemblages, combined with elevated silica concentrations, are diagnostic of high-temperature alteration zones. The vertical mineralogical evolution inferred from the XRD patterns indicates compositional variability with increasing depth, transitioning from shallow clay-rich horizons to deeper carbonate–silica assemblages. This transition reflects progressive thermal alteration and recrystallization within the geothermal reservoir environment. The coexistence of dolomite and quartz implies potential for enhanced permeability and fluid transmissivity, particularly where alteration and fracturing coincide. Overall, the geochemical and mineralogical results from the YDS-1 well suggest the presence of a thermally mature, silica-dominant reservoir system with significant alteration signatures that support geothermal activity at depth. These findings contribute to the development of a conceptual reservoir model for the study area, providing a baseline for future hydrothermal circulation modeling, geochemical monitoring, and stimulation design to enhance reservoir performance and promote sustainable utilization..

4.3 Seismic Investigations and Structural Assessment

While existing MT surveys have effectively constrained the cap rock and reservoir horizons, they provide limited information on the subsurface geometry of discontinuities. To refine structural interpretation, seismic investigations are proposed as a complementary method to delineate fault systems, fracture corridors, and reservoir boundaries in three key areas: Güzelkent, Kargapazarı, and Ilıpınar. Reflection seismic profiling will help determine reservoir thickness and extent, while refraction methods will enhance understanding of shallow stratigraphy and layer continuity. Integrating seismic data with existing MT and geochemical datasets enables the construction of a three-dimensional conceptual model that links structural permeability, thermal anomalies, and geochemical gradients. A comprehensive geophysical survey was conducted to assess the geothermal potential within the IGNIS license fields near Bingöl-Karlıova. Gravity data were collected from 303 stations, and magnetotelluric (MT) data were acquired from 623 MT stations, with 459 used for modeling, covering over 100 km^2 (Figure 4). These datasets were processed using 3D inversion to generate resistivity models, vertical cross-sections, and depth-slice maps. The MT results depict a stratified subsurface consisting of three main geo-electrical layers: a shallow high-resistivity zone, an intermediate low-resistivity layer interpreted as cap rock, and a deeper high-resistivity reservoir unit. Structural patterns and thermal manifestations indicate that geothermal fluid circulation is strongly controlled by active fault zones associated with the KTJ.

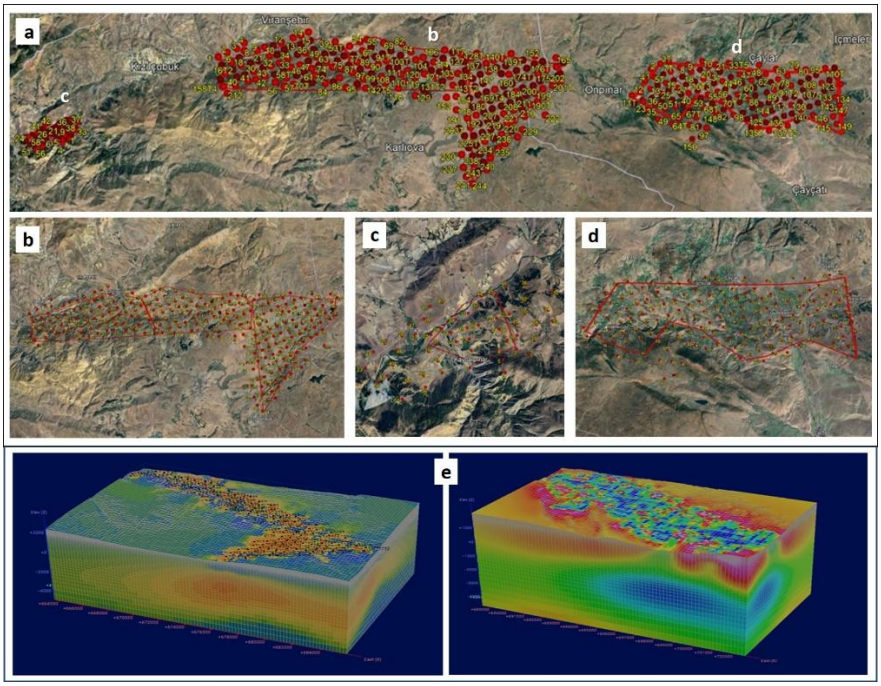


Figure 4. a) general view of stations of b) Karlıova, c) Kaynarpınar, d) Güzelkent, e) results of the gravity and magnetotelluric (MT)

A lateral comparison of the fields shows that Kargapazarı has a resistivity structure highly similar to that of the previously studied Güzelkent field, suggesting geological continuity. In contrast, the Kantarkaya and Ilıpınar sites display a similar electrical structure but with a significantly shallower potential. Multiple N-S, NE-SW, and E-W oriented faults were modeled and are believed to control the lateral thickening and deepening of the conductive cap layer, particularly toward the eastern part of the study region. All MT data obtained have been evaluated as 3b. The investigation revealed the presence of units with low resistivity values in the area, observed at depths of 2,000–3,000 m. It is evident that drilling at this depth in the area will yield good results (Figure 6). Based on combined structural and resistivity evidence, several priority drilling zones were identified across the Ilıpınar, Kantarkaya, and western Kargapazarı fields. Exploratory drilling is planned for Q2, Q3, and Q4 of 2026 in the license areas.

5 CONCLUSIONS

This integrated geological, geophysical, and hydrogeochemical assessment of IGNIS licenses demonstrates that the Karlıova region hosts a structurally controlled and thermally active geothermal system within the deformation zone of the Karlıova Triple Junction. Magnetotelluric resistivity models reveal a stratified subsurface architecture, with a conductive caprock overlying high-resistivity reservoir units, while fault intersections and transtensional zones serve as key permeable pathways enabling deep fluid circulation. Hydrothermal alteration signatures and preliminary water chemistry results further support the presence of a promising geothermal resource. To validate reservoir characteristics and reduce subsurface uncertainty, future work will focus on high-resolution seismic imaging, targeted exploratory drilling, and continued geochemical monitoring. These outcomes provide a critical foundation for advancing resource sustainability and guiding geothermal investment in Eastern Anatolia.

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