

Impact of Stratigraphically Unpositioned Saline Units on Electrical Resistivity in Geothermal Potential Investigations: Case Study Area Eldivan (Çankiri, Türkiye)

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Abstract

Since 1968, geothermal energy utilization in Turkey has increased rapidly due to the country's significant geological potential. This study aims to evaluate the geothermal potential of the Eldivan region, focusing on subsurface characteristics. Initial analyses indicated a high geothermal gradient at a depth of 900 meters. However, further investigations revealed the presence of previously unmapped and stratigraphically unpositioned saline units, which are identified as the primary cause of low resistivity anomalies observed in Vertical Electrical Sounding (VES) data. Hydrogeochemical analysis of water samples collected from the Gözdöken Spring confirmed the presence of high sodium (1071 mg/L) and chloride (585 mg/L) concentrations, supporting the existence of these saline units. Using the Fournier & Rowe (1966) quartz geothermometer, a reservoir temperature of 61.88°C was estimated, indicating a low- to medium-enthalpy geothermal system. These findings underscore the necessity for more detailed and integrated approaches to accurately assess the geothermal energy potential of the region.

Keywords

Eldivan, Vertical Electrical Soundings, Geothermal, Resistivity

1. Introduction

The heat source in a geothermal system is essential for harnessing geothermal energy. To utilize this heat, a carrier such as liquid, gas, or steam must transport it to the surface through a crack system (Ozgener & Hepbasli, 2007). Geothermal

systems rely on the geothermal gradient and the circulation of fluids to transfer heat to the surface (Lund, 2010). Turkey is located in a tectonically active zone and possesses geological features associated with recent magmatism and volcanism, fulfilling all the necessary requirements for geothermal systems (Aydın et al., 2005). These geological properties contribute to the significant geothermal energy potential in Turkey, with regions such as Southeastern Anatolia and Western Anatolia being highlighted for their geothermal resources (Baba & Chandrasekharam, 2022; Baba et al., 2019). Additionally, the seismic activity in the Anatolia region plays a crucial role in Turkey's high level of geothermal energy potential (Rabet et al., 2017).

The Çankırı-Çorum Basin in Turkey is known for its abundance of low-temperature geothermal resources, such as Çavundur and Kurşunlu (Düşünür-Doğan & Üner, 2019). The basin has undergone significant geological transformations due to tectonic activities. Studies have revealed that the basin's geological history dates back to the Late Cretaceous-early Cenozoic period, marked by the closure of the Neotethys Ocean (Métais et al., 2016). The basin is known for its Neogene age and the presence of evaporitic formations, making it a crucial area for understanding the geological evolution of Central Anatolia (Horasan & Öztürk, 2021). The western margin of the Çankırı Basin has experienced tectonic-sedimentary developments characterized by faulted and thrust margins (Seyitoğlu et al., 2004).

The research site is situated within this basin in Central Anatolia, Turkey, as depicted in Figure 1. The geological composition of the study area is depicted in Figure 2, which features the Eldivan ophiolites at its foundational layer, resulting from the previously mentioned tectonic collision. Overlying this foundation is a substantial fill, measuring up to 4 kilometres in thickness, comprised of sedimentary rocks that span a diverse range of ages and types, from the Late Cretaceous period through to the Late Pliocene epoch (Ileri, 2007; Bölük, 2013; Çelik et al., 2013; Üner et al., 2014). The tectonic features within the study area were formed under the influence of the North Anatolian Fault Zone (NAFZ) and the adjacent suture zone. Additionally, Miocene-Pliocene volcanic rocks are situated in proximity to this region (Seyitoğlu et al., 2004; Bölük, 2013; Karadenizli, 2011).

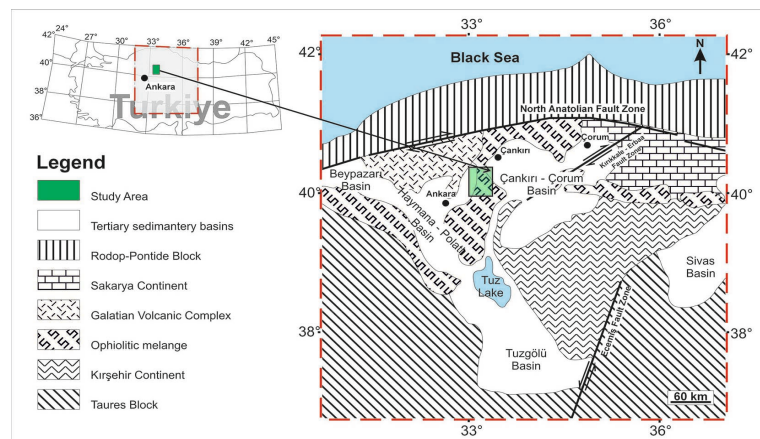


Figure 1. Location map of the study area (revised from Karadenizli, 2011).

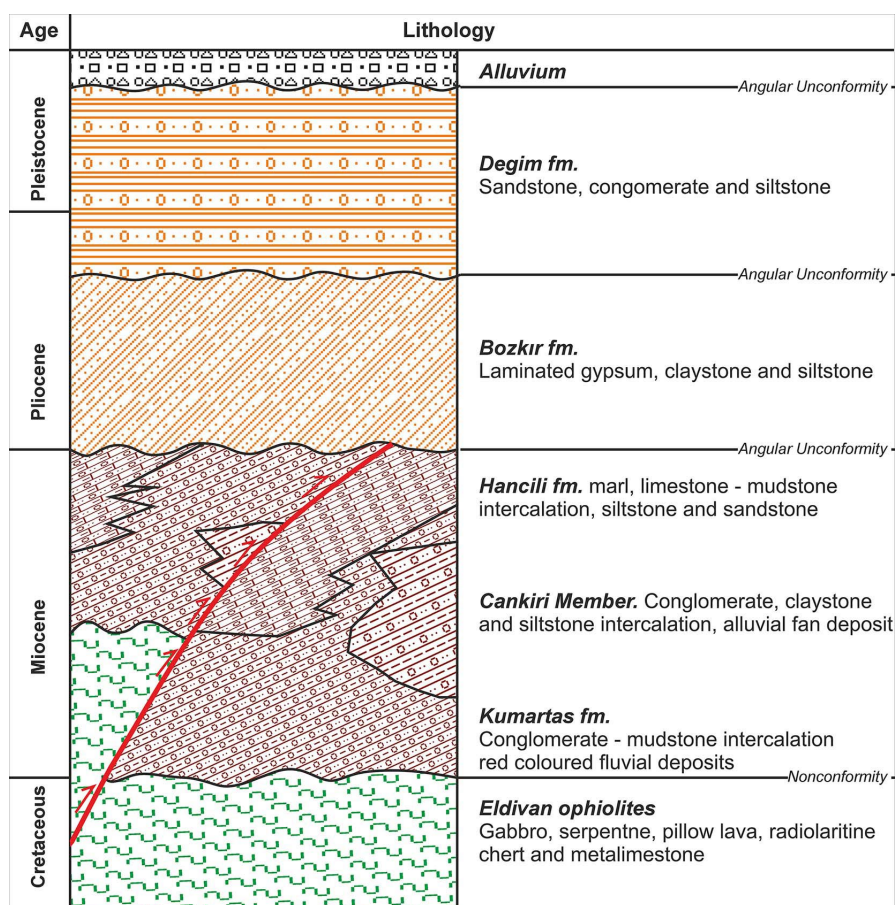


Figure 2. The generalized tectonostratigraphic sequence of the study area (not scaled) (revised from Bölük, 2013; Karadenizli, 2011).

This study is critical in guiding more detailed and consequently costlier research efforts to determine and characterize the geothermal potential in the Eldivan region. Initially, it laid a solid foundation for accurately directing further investigations, necessitating detailed studies through research drilling or deep geophysical methods such as Magnetotelluric (MT) suitable for the region's geology. However, upon re-examining the data, previously unmapped saline units were identified at the depth considered to have geothermal potential. These findings necessitate a reevaluation of the region's geothermal prospects.

In light of this new information, the need for more refined methods becomes evident, as these saline units could significantly influence the assessment of geothermal resources. This study's Vertical Electrical Sounding (VES) method remains crucial for conducting deep resistivity measurements in the Eldivan (Çankırı) region. This method is vital for detecting underground water and steam presence and determining the physical properties of rocks, such as permeability and porosity, which are essential for geothermal exploration. However, the presence of saline units underscores the importance of incorporating additional geophysical techniques or more detailed drilling to accurately map these formations and reassess the area's geothermal potential.

2. Geological Settings

2.1. Stratigraphy

The Çankırı-Çorum Basin in Turkey has been shaped by complex tectonic processes, including the closure of the Neo-Tethys and the formation of the Izmir-Ankara-Erzincan suturing zone. The tectonic features of the basin have been influenced by the North Anatolian Fault Zone (NAFZ) and the suture area, leading to the development of young volcanic rocks in the vicinity (Korkmaz et al., 2022). The collision along the Hellenic-Cyprian Tectonic Arc during the neotectonics period has played a significant role in the tectonic evolution of the region, leading to the initiation of a tectonic regime dominated by strike-slip faults during the Paleocene-Early Eocene (Korkmaz et al., 2022).

The closure of the Paleo- and Neo-Tethys oceans, subduction, collision, extension, uplift, and strike-slip faulting have contributed to the tectonic properties and structural evolution of the area (Üner et al., 2014; Karaoğlan et al., 2012; Moix & Goričan, 2013; Özaydın et al., 2018). The basin has experienced sedimentation and deformation, transforming into foreland basins, with the Çankırı basin and its eastern extension continuing to sediment into the early Lutetian period (Akçay & Beyazpirinç, 2017). The suture zone in the basin elevated above sea level and experienced significant erosion until the end of the early Eocene (Karadenizli, 2011; Akçay & Beyazpirinç, 2017).

2.2. Eldivan Ophiolites

The Eldivan area in the Çankırı-Çorum Basin is characterized by the presence of ophiolites overlain by Neogene formations, which are typically deposited in fluvio-lacustrine conditions and alluvial fan deposits (Figure 3). The granitoids located a few kilometres west of the survey area serve as the heat source for the geothermal system. Additionally, the area exhibits North-South striking very low-angle thrust and normal faults and East-West striking strike-slip faults with high inclination.

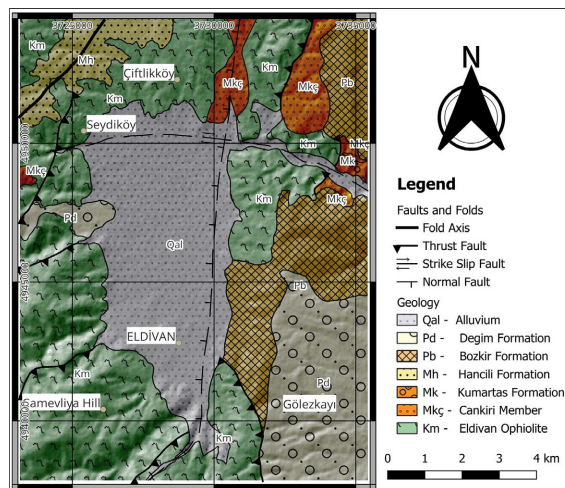


Figure 3. Geology map of study area (revised from Bölük, 2013; Karadenizli, 2011; Akyürek et al., 1980).

The Eldivan ophiolite has been recognized as a significant geological feature, forming a bridge between discontinuous outcrops of Upper Jurassic ophiolites in the Hellenide-Dinarides to the West and those of Armenia and Iran to the East. The geochemical and isotopic characteristics of the Eldivan ophiolite have been studied to understand its origin and its role in the broader tectonic framework. Additionally, the Eldivan ophiolite has been associated with the Ankara Mélange, providing insights into the Tethyan evolution of Anatolia (Üner et al., 2014; Çelik et al., 2013).

2.3. Miocene Units

In the current investigation, an exhaustive examination and delineation of the geological units within the Eldivan region have been undertaken. The stratigraphic succession reveals a foundational ophiolitic basement, succeeded by the Kumartaş, Bozkır, and Değim formations, ranging chronologically from the Early Miocene to the Pleistocene epoch (refer to **Figure 2** and **Figure 3**). These Neogene stratigraphic entities were predominantly deposited under fluvio-lacustrine regimes, supplemented by alluvial fan sediments, with contemporary alluvium draping all pre-existing units.

Northward of the study area, the Kumartaş formation, a veneer over the ophiolites, is discernible. It comprises brown conglomerates, mudstones, and sandstones, dating to the Early to Middle Miocene. The formation is interpreted as fluvial fan deposits, evidenced by channel fills (Akyürek et al., 1980).

Adjacent to the north of the study area, the Cankırı member manifests a transitional contact, both laterally and vertically, with the Kumartaş and Hançili formations. This member is characterized by an alternation of conglomerates, sandstones, and mudstones, and is dated to the Middle Miocene. It exhibits properties emblematic of classical fan deposits (Karadenizli, 2011).

The Hançili formation is distinguished by its grey and green marl-mudstone alternations, in addition to siltstone, conglomerate, and sandstone layers, attributed to the Middle Miocene. This formation is indicative of a lacustrine environment and is noted for its organically rich levels (Akyürek et al., 1980).

2.4. Pliocene and Pleistocene Units

Superseding Paleocene formations, the Bozkır formation, demarcated by an angular unconformity, consists predominantly of gypsum and anhydrite with a characteristic white hue and dates back to the Lower to Middle Pliocene.

The Neogene's youngest formation, the Değim, is positioned atop the Bozkır formation, marked by an unconformity. It is composed of sandstones and conglomerates, featuring distinctive brown and red hues, and is dated to the Upper Pliocene to Lower Pleistocene. This formation exemplifies the properties of alluvial fans, braided fluvial systems, and floodplain deposits. Overlying these units is alluvium, centrally located within the study area (Akyürek et al., 1980).

2.5. Tectonics

The basin and study area's principal tectonic regime is influenced by the North Anatolian Fault (NAF). A prevalent structural feature is the low-angle dip thrust fault (**Figure 4**).

The most widely accepted model for these thrust faults is the tectonic sliver model, which suggests that the Eldivan Ophiolitic Mélange was emplaced upon Neogene formations and, occasionally, upon itself (Ileri, 2007).



Figure 4. Thrust fault surfaces and slip striations observed within Eldivan Ophiolites.

This tectonic activity, driven by nearly east-west directed compression, resulted in the formation of thrust faults, with concurrent formation of normal faults on the opposing side of the tectonic sliver. These thrust faults exhibit an NNE-SSW trend, traceable within the study area and discernible beneath the alluvium through electrical resistivity-derived structural maps. Similarly, SP logs corroborate the location of these faults. Given the prerequisite for geothermal systems to exploit fracture systems, typically faults, and their frequent occurrence near the intersection of multiple fault lines, the study area near the intersection of the nearly E-W trending Yanlarbogazi fault, N-S trending normal and strike-slip faults which is covered by alluvium in study area and N-S trending thrust fault is notably significant (**Figure 5**).

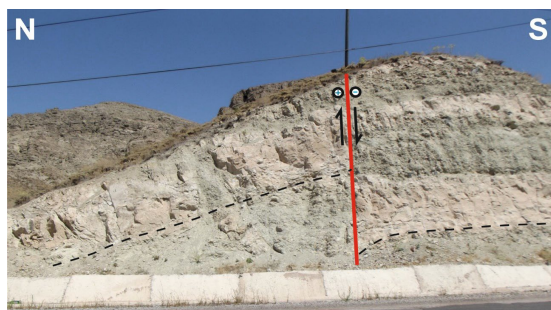


Figure 5. The appearance of the Yanlarbogazi Fault within the study (View from the East).

2.6. Water Chemistry

Hydrogeochemical analysis of a water sample taken from the Gözdöken Bağları area (near VES 3) has been conducted, and it was found to have a high electrical conductivity. Conductivity, a function of the dissolved ion content in water, is considered an indicator of geothermal activity. Additionally, high levels of dissolved Na, Cl, Mg, and SO₄ in the water suggest the presence of units containing gypsum and anhydrite (Bozkır formation), which are indicative of extensive areas, either stratigraphically or tectonically positioned at depth. The analysis of the sample was (Table 1) interpreted using a Piper diagram (Figure 6), and the water was classified as belonging to the Mixed type (Bölük, 2013).

Table 1. Analysis of water sample from Gozdoken Spring (Bölük, 2013).

Parameter	Value
pH	6.60
Eh (mV)	275
Dissolved O ₂ (mg/l)	2.1
EC (µS/cm)	5360
K (mg/l)	51.05
B (mg/l)	12.31
Cu (mg/l)	<0.01
Pb (mg/l)	<0.01
SO ₄ ²⁻ (mg/l)	120
NO ₂ ⁻ (mg/l)	0.09
HCO ₃ ⁻ (mg/l)	3208
Total Hardness (°f)	104.4 (very hard)
Ca (mg/l)	281
Mg (mg/l)	78.38
Na (mg/l)	1071
Si (mg/l)	19.18
As (mg/l)	1.96
Fe (mg/l)	<0.01
Zn (mg/l)	<0.01
NO ₃ ⁻ (mg/l)	<4.4
Cl ⁻ (mg/l)	585

Based on Fournier & Rowe's (1966) quartz geothermometer, the estimated reservoir temperature is approximately 61.88°C, calculated using the formula:

$$T(^{\circ}\text{C}) = \frac{1309}{5.19 - \log(\text{SiO}_2)} - 273.15$$

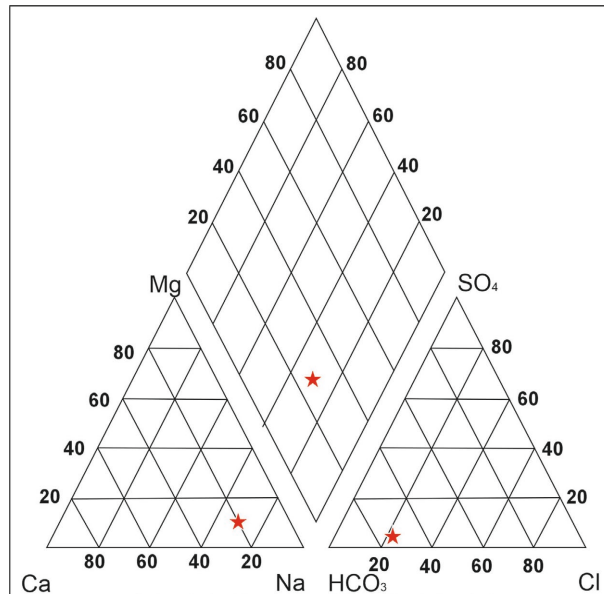


Figure 6. The position of the water sample taken from the Gözdöken Bağları area on the Piper diagram (Bölük, 2013).

where the dissolved silica concentration (SiO_2) is 19.18 mg/L (Fournier & Rowe, 1966). This moderate temperature suggests a potential low-enthalpy geothermal system, which may be suitable for applications such as direct-use heating rather than high-enthalpy applications like electricity generation. Thus, the water type can be interpreted as a warm source rather than a hot source, characterized by conditions typical of shallow geothermal systems where dissolved quartz equilibrates at relatively lower temperatures.

3. Geophysical Surveys

3.1. Vertical Electrical Resistivity

The electrical resistivity method, leveraging direct or low-frequency alternating currents to probe subsurface properties, is a cornerstone in geophysical and environmental research. Its applications span soil science, aquifer mapping, identifying subsurface anomalies, evaluating sites for solid waste disposal, and permafrost studies (Salman et al., 2020). The method stands out for offering semi-accurate subsurface images and efficiently mapping resistivity variations, crucial for groundwater exploration and hydrogeological investigations (Santi et al., 2022).

Vertical Electrical Soundings (VES) remain a widely used method for groundwater exploration in developing countries due to its cost-effectiveness, speed, and equipment simplicity (Okoro et al., 2010; Hussain et al., 2016). The VES method has been successfully employed in various studies, including evaluating aquifer characteristics, delineating saltwater and freshwater aquifers, and protective capacity assessment of vadose zone material (Hodlur et al., 2006; Chikabvumbwa et al., 2021).

Additionally, VES has been utilized for geophysical investigations of dambo

groundwater reserves for sustainable irrigation water sources and groundwater exploration in different regions (Chikabvumbwa et al., 2021; Shanshal, 2018). The simplicity and low cost of the VES method make it accessible and effective for assessing groundwater resources in diverse geological and hydrogeological settings (Hodlur et al., 2006; Chikabvumbwa et al., 2021; Shanshal, 2018). The method's versatility and applicability have been demonstrated in studies focusing on aquifer characteristics, protective capacity assessment, and groundwater exploration, highlighting its significance in addressing water resource management challenges in developing countries (Okoro et al., 2010; Hussain et al., 2016; Chikabvumbwa et al., 2021; Shanshal, 2018).

This method fundamentally relies on measuring the potential change caused by a current applied to the ground. The resistance is obtained through Ohm's law using the measured current and potential values (Figure 7). Given that the material being measured, such as rock and soil, is complex in nature and that the measurement needs to be positioned in three dimensions, a geometric correction factor is applied to obtain the apparent resistivity for the chosen configuration.

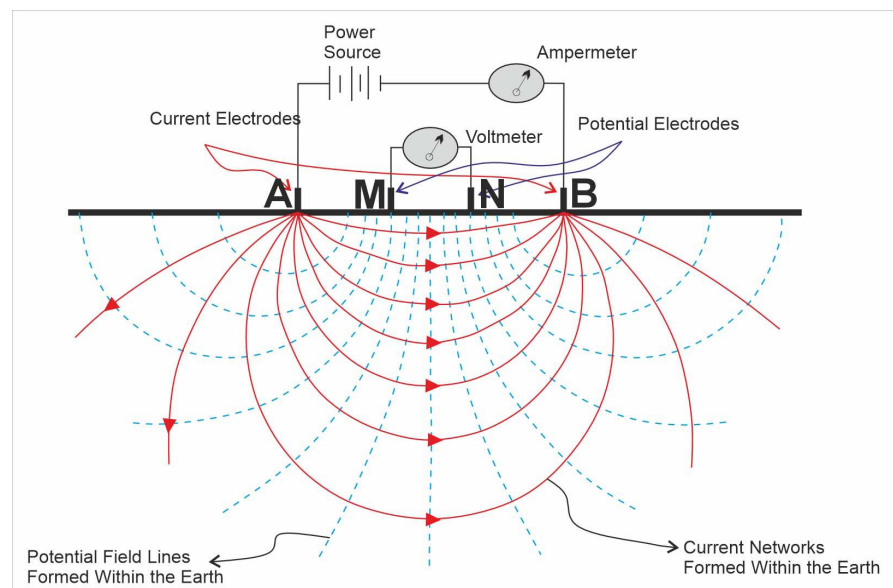


Figure 7. General configuration of the four surface electrodes in resistivity surveys. A and B electrodes, to deliver current, M and N potential electrodes for voltage readings.

The Schlumberger array is a commonly used configuration for conducting VES, allowing for the determination of subsurface resistivity variations and the characterization of aquifer systems in diverse geological settings. This method has been widely applied in groundwater exploration, hydrogeological studies, and environmental assessments, demonstrating its versatility and effectiveness in subsurface investigations (Okoro et al., 2010; Dawoud & Raouf, 2009; Akhter & Hasan, 2016; Lukuman, 2019). Due to its simplicity and cost-effectiveness, the Schlumberger-array-based VES method is particularly valued in developing regions, promoting accessible and affordable subsurface exploration (Kasidi, 2017). Its capacity to

elucidate subsurface lithology, aquifer properties, and groundwater availability makes it an essential instrument for water resource management and environmental evaluations.

In the present investigation, the resistivity measurements were conducted using state-of-the-art equipment specifically engineered for direct current (DC) geophysical surveys. The apparatus comprises a generator with a capacity of 10 kW, serving as the primary electrical source. To accommodate varying subsurface resistivity conditions, the system is equipped with a variac unit, allowing for the adjustment of voltage and current parameters up to a maximum of 2000 V and 2 A, respectively (**Figure 8**). This facilitates the enhancement of signal penetration depth and resolution in diverse geological settings. The measurement precision is further ensured by deploying a pair of multimeters, characterized by a sensitivity of 0.1 mV and 1 mA. This high degree of sensitivity is pivotal for detecting subtle variations in subsurface resistivity, thereby enabling a detailed delineation of geological formations and structures critical to the assessment of geothermal potential.



Figure 8. High voltage and high current capacity direct current geophysical device used in this study.

3.2. Review of Existing Geophysical Data

Prior geophysical explorations conducted by the General Directorate of Mineral Research and Exploration (MTA) in the study area have laid a foundational understanding of subsurface anomalies (Karadenizli, 2011; Akyürek et al., 1980). These preliminary studies have identified notable anomalies, prompting a reevaluation in the context of the presence of mineral waters in Eldivan. To build upon this existing knowledge, the author's master thesis project has established a 1 km interval grid (**Figure 9**), extending up to 1500 metres (max), across which 19 Vertical Electrical Sounding (VES) were carried out (**Figure 9**).

Among these, an anomaly detected at the VES point 3 has sparked particular interest. However, the proximity of the used equipment's effective depth to the anomaly's depth, coupled with the geological presence of evaporitic units at the anomalous point, underscores the necessity for further measurements from new

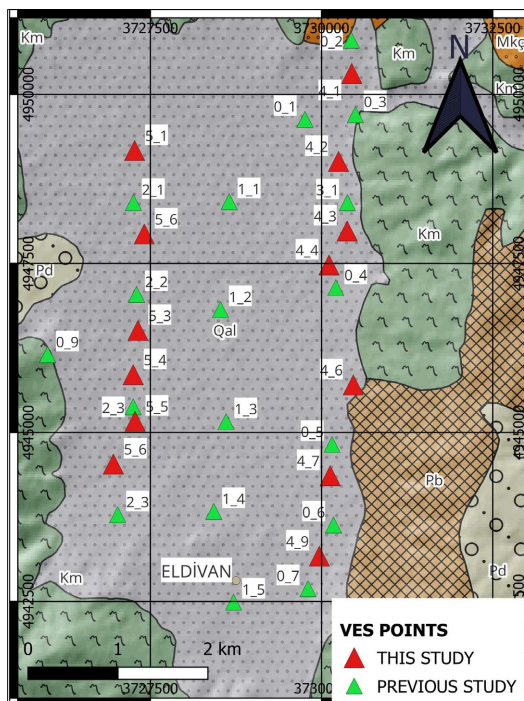


Figure 9. Location map of VES points gathered from study area.

and deeper locations. This endeavor not only aims to refine our understanding of the identified anomalies but also seeks to elucidate the geophysical characteristics contributing to the area's mineral water presence, thereby enhancing the geological model of Eldivan with a focus on its geothermal potential.

3.3. New Geophysical Data

This research presents an in-depth analysis building upon the authors' previous investigations in Eldivan, focusing on the geophysical exploration of the area with a depth limitation of up to 1500 metres. The initial study highlighted three sites as promising for potential geothermal exploration. However, the stratigraphic characteristics of the study area indicated that shallow low resistivity zones might originate from evaporitic units present in the Bozkır formation and deep low resistivity zones might originate from chrome-rich levels of the ophiolitic basement.

To refine the understanding of the geothermal potential, this study introduces new data from 17 Vertical Electrical Soundings (VES) extending down to a depth of 3000 metres. In this study, the selected new points were strategically positioned to coincide with the midpoints between previously surveyed locations, which were spaced 1 km apart. This adjustment was made with the aim of enhancing the resolution of the data obtained.

RMS error rate of 10% or lower has been subjected to interpretation. In the graphs derived from these measurements, a key focus is to observe any decrease and subsequent increase in apparent resistivity values, particularly beyond the approximate depth of the Neogene units (**Figure 9**). In the evaluated graphs, anomalies expected in a geothermal area have been encountered in VES 4.2 and VES

4.3 (Figure 10). A low resistivity zone has been observed, which could be an aquifer containing hot and/or mineralized water.

When the data obtained from the interpretation of VES 4.4, VES 4.6, VES 5.2, VES 5.3, VES 5.4 and VES 5.5 curves are evaluated, it is observed that they do not show the anomalies we aimed to identify in our study. While the interpretation of these curves can assist in determining the boundaries of the stratigraphic units in the region, they do not contain low resistivity anomalies that could indicate geothermal potential. VES 4.4 and VES 4.6 are significant in showing evaporitic levels at ~250 - 400 m depth, while the boundaries between ophiolite and Neogene units are observed between 500 and 700 metres in the others (Figure 10). Upon evaluating the data obtained, 12 Vertical Electrical Sounding (VES) measurements with a Root Mean Square. In addition to these, the anomaly observed at greater depths in VES 5.1, VES 5.6, and VES 5.7 likely corresponds to the thrust ends associated with the tectonic structure known as the Eldivan Thrust Wedge (Ileri, 2007).

The relative resistivity drops at approximately the same depth (around 1000 m) in these measurements indicate the boundary between the ophiolites and the overlying unit, which raises the main question. While this anomaly could indicate a low-temperature mineral water source, it may also suggest the presence of saline units that have not been previously included in the stratigraphic sections, as they do not outcrop in the region but could be observed over a wide area along the study site.

The existence of these hypothesized saline units is plausible, considering the western part of the study area has been downthrown by normal faults, and it could also explain the high Na and Cl content found in the Gozdoken spring.

4. Results

The previous investigation executed nineteen Vertical Electrical Soundings (VES) extending to depths up to 1500 meters. This effort created multiple profiles to refine our understanding of the underlying geothermal structure. Consequently, VES 3.1 was identified as having a potentially high geothermal gradient at a depth of 900 metres. However, it was noted that this anomaly at 900 metres could be attributed to saline layers. Due to this consideration, additional VES surveys were carried out in the study area.

Building upon this foundation, the current study assessed seventeen measurements, focusing on the twelve with a Root Mean Square (RMS) error of 10% or lower. These were evaluated in conjunction with previous geophysical research and the geological, tectonic, and hydrogeological context of the region, thereby identifying areas with potential significance.

The measurements revealed that the potential sites identified by VES anomalies in previous studies are not attributed to saline units but originate from mineralized waters. This conclusion is drawn from the observation that almost all graphs exhibit a decrease followed by an increase in apparent resistivity values between 250 and 500 metres depth. Furthermore, the thickness of the Neogene units, as

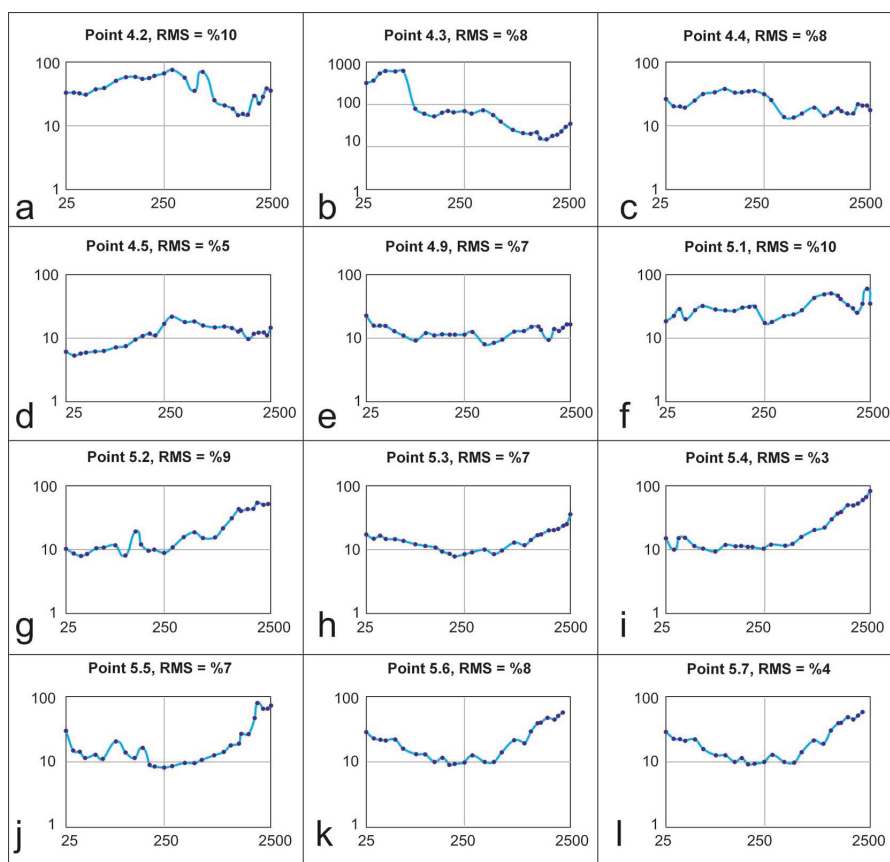


Figure 10. VES graphs drawn with the measurements taken in this study.

indicated by these graphs, corresponds to depths between 500 - 750 metres. Consequently, the potential geothermal source is at a shallower depth than initially anticipated.

Particularly when examining VES 4.2, located very close to the previously identified VES 3.1 point, the anomaly formed between 900 and 1200 metres indicates that drilling to a depth of 1200 - 1300 metres in this area would yield hot and/or mineralized fluid. This location, which is also near the Gözdöken source, a known mineral and warm water source in the area, suggests it as the most suitable point for exploratory geothermal drilling. This conclusion is supported by calculating a 61.8°C reservoir temperature based on the Si content in the water sample taken from this source (Fournier & Rowe, 1966), and the potential association with the faults.

5. Conclusion

In conclusion, when all VES data are interpreted with geological and tectonic observations, the geological model of the study area becomes clearer, as demonstrated in **Figure 10**. It can be seen that the relative resistivity drop observed at around 1000 m depth likely marks the boundary between ophiolites and the overlying unit. This anomaly could indicate a low-temperature mineral water source or previously uncharted saline units in the region (**Figure 11**). The existence of

these saline units is plausible, especially given the tectonic downthrow to the west of the study area, and may also explain the high Na and Cl content found in the Gözdöken spring.

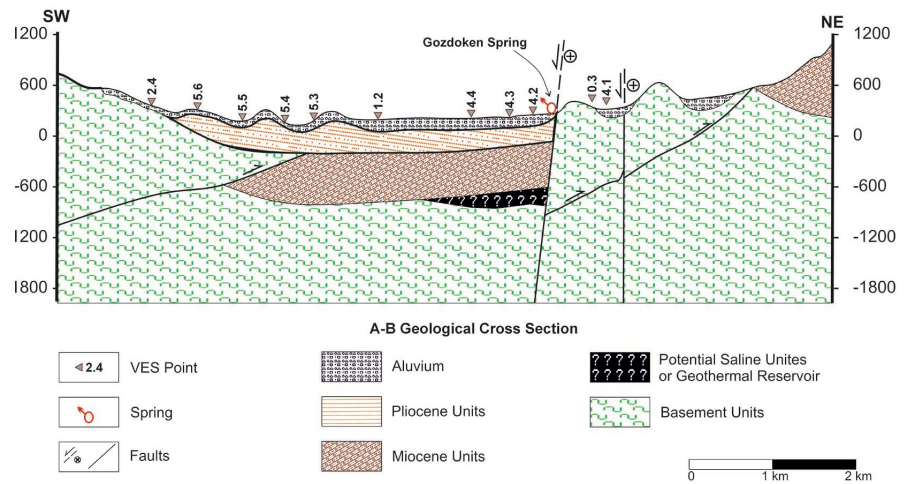


Figure 11. Geological conceptual model of the study area.

After this study, it is emphasized that research drilling, magnetotelluric (MT) methods, and detailed hydrogeological studies are strongly recommended for a more detailed examination of the geothermal potential in the Eldivan region. The preliminary findings presented here serve as a guide for future research, directing exploratory efforts that include advanced geophysical techniques and drilling operations capable of uncovering the full extent of geothermal energy resources in the area. By facilitating an in-depth analysis of the region's geothermal resources, these methods will allow for a more accurate assessment of Eldivan's geothermal energy potential.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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