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Integrated VES and GPR Investigation of Clay-Rich Units in the Çukurçeşme Formation (Şile, Istanbul)

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Abstract

The present study reviews the subsurface distribution and geometry of clay-rich strata within the Oligo–Miocene Çukurçeşme Formation in the Şile area (Istanbul) using an integrated methodology combining Vertical Electrical Sounding (VES) and Ground Penetrating Radar (GPR). A total of 30 VES measurements were obtained and analyzed by 1D inversion, and the resultant models were assembled into 2D pseudosections to designate laterally continuous conductive layers. Low-resistivity zones seen across the profiles were interpreted as clay-dominant, aquiferous strata based on their distinctive electrical response and field observations. GPR data acquired with a 38–50 MHz antenna yielded high-resolution insights into the near-surface strata. Radargrams displayed continuous, moderately inclined reflectors indicative of the upper margins of clayey strata; however, signal attenuation restricted imaging at deeper levels. The integration of VES-derived resistivity structure with GPR reflections improved the interpretation of the clay layer's geometry and revealed thickness variations throughout the study area. The aggregated findings demonstrate that clay-rich strata often occur at depths of approximately 5 to 40 meters, with localized thickening influenced by structural and depositional factors. The concordance between VES and GPR interpretations enhances the credibility of the subsurface model generated in this work. This study demonstrates the efficacy of combining VES and GPR techniques to characterize diverse near-surface formations in regions where clay predominates, thereby influencing electrical and electromagnetic responses. The results establish a geophysical framework for subsurface characterization in analogous geological contexts and facilitate future research to enhance the stratigraphic and structural understanding of the Çukurçeşme Formation.

Key words: Clay deposits, Çukurçeşme Formation, vertical electrical sounding, ground penetrating radar, geophysical methods.

Resumen

Esta investigación se enfoca en la distribución y la geometría subsuperficiales de los estratos ricos en arcilla de la Formación Çukurçeşme, perteneciente a la etapa Oligoceno-Mioceno, en el área de Şile (Estambul), mediante una metodología integrada que combina Sondeos Eléctricos Verticales (VES) y Radar de Penetración Terrestre (GPR). Se obtuvieron un total de 30 mediciones de SEV, las cuales fueron sometidas a análisis mediante inversión 1D, y los modelos resultantes se incorporaron en pseudosecciones 2D con el objetivo de identificar capas conductoras de continuidad lateral. Las áreas de resistividad reducida identificadas a lo largo de los perfiles se interpretaron como estratos dominados por arcilla y de naturaleza acuífera, con base en su respuesta eléctrica singular y en las observaciones de campo. Los datos de GPR, obtenidos con una antena de 38–50 MHz, proporcionaron información de alta resolución sobre los estratos someros. Los radargramas exhibieron reflectores continuos y de inclinación moderada, lo que señala los márgenes superiores de los estratos arcillosos; sin embargo, la atenuación de la señal restringió la captura de imágenes a profundidades mayores. La incorporación de la estructura de resistividad derivada de los SEV, junto con las reflexiones obtenidas mediante la metodología GPR, optimizó la interpretación de la geometría de la capa arcillosa y facilitó la identificación de variaciones de espesor a lo largo de todo el ámbito de estudio. Los hallazgos integrados indican que los estratos con alta concentración de arcilla suelen manifestarse a profundidades entre 5 y 40 metros, con engrosamientos localizados regulados por factores estructurales y deposicionales. La congruencia entre las interpretaciones derivadas de los Sistemas de VES y del GPR potencia la confiabilidad del modelo subsuperficial desarrollado en este estudio. Esta investigación evidencia la eficacia de la combinación de las técnicas VES y GPR para la caracterización de formaciones someras heterogéneas en regiones donde predominan las arcillas, factores que determinan la respuesta eléctrica y electromagnética. Los hallazgos configuran un marco geofísico para la caracterización del subsuelo en contextos geológicos similares y proporcionan un fundamento para investigaciones posteriores orientadas a mejorar la comprensión estratigráfica y estructural de la Formación Çukurçeşme.

Palabras clave: depósitos de arcilla, Formación Çukurçeşme, sondeo eléctrico vertical, radar de penetración terrestre, métodos geofísicos.

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1. Introduction

Clay deposits are essential industrial raw materials due to their exceptional plasticity and wide range of applications, especially in the ceramics, cement, paper, and brick sectors (Dondi *et al.*, 2025). Turkey has abundant clay resources; however, many deposits are inadequately described, underscoring the need for comprehensive geological and geophysical studies to facilitate sustainable use. The Şile region, situated northeast of Istanbul, is among Turkey's most attractive sites because of its high-quality clay deposits linked to the Oligo–Miocene Çukurçeşme Formation, a diverse sequence of clay, sand, and gravel (Demir, 2021).

Conventional drilling techniques yield precise subsurface data but are expensive, labor-intensive, and geographically constrained, rendering them inadequate for extensive mapping of clay deposits. Thus, the incorporation of geophysical technology has become a crucial method for ascertaining the depth, lateral continuity, and structural attributes of subsurface clay-rich formations. Multiple studies have evidenced the efficacy of electrical and electromagnetic techniques in addressing near-surface geological intricacies (Akingboye *et al.*, 2022; Butt *et al.*, 2025; Najaftomraei *et al.*, 2024).

Electrical resistivity methods are frequently employed to detect conductive units, such as water-saturated clay layers, due to their unique electrical fingerprints (Aweto & Mamah, 2014; Loke *et al.*, 2014, 2022). While Electrical Resistivity Tomography (ERT) is widely used for 2D and 3D imaging and has demonstrated efficacy in multilayered settings (Loke *et al.*, 2022; Pellicer & Gibson, 2011), Vertical Electrical Sounding (VES) remains a reliable technique for depth profiling in stratified landscapes. Prior studies (Al-Zubedi & Thabit, 2014; Al-Hameedawi & Thabit, 2017; Yalçın, 2025; Yalçın, 2026) have demonstrated that electrical techniques are dependable for identifying vertical variations in subsurface resistivity, a crucial sign of clay-dominated and conductive strata.

Ground-Penetrating Radar (GPR) provides high-resolution supplementary data, particularly for shallow subsurface formations, thereby facilitating the accurate identification of near-surface boundaries and sedimentary stratigraphy (Pellicer *et al.*, 2014, 2016). Despite rapid attenuation in water-saturated clays, GPR penetration can be enhanced by integrating it with resistivity-based methods, thereby enhancing subsurface characterization by combining depth sensitivity with high-resolution imaging (Farias *et al.*, 2023).

Global applications demonstrate that integrated electrical and radar techniques are proficient in delineating clay deposits, aquifer zones, karst characteristics, and construction materials (Drahor & Berge, 2017; Farias *et al.*, 2023). Şans *et al.* (2024) highlighted the geological significance of clay assemblages in the Paleozoic and younger strata of the Şile region, underscoring the necessity for comprehensive subsurface characterisation.

This study aims to delineate the subsurface structure, depth, and thickness of clay-rich layers within the Çukurçeşme Formation in the Şile region using a combination of VES and GPR techniques. This work enhances understanding of the spatial distribution of clay deposits by integrating the depth penetration of VES with the high-resolution imaging of GPR. The results enhance regional geological knowledge and guide future research in analogous geological contexts, especially for assessing the industrial viability of clay-rich formations.

2. Geological Background

The Şile area, situated northeast of Istanbul, has a diverse geological composition, particularly from the Paleozoic era (Okay *et al.*, 1994; Yılmaz *et al.*, 1997; Okay and Kylander-Clark, 2023). The area comprises sedimentary rocks and volcanic formations from multiple epochs, and it contains high-quality clay deposits formed by the erosion of these rocks (Akyüz, 2010). The geological structure of Şile features an extensive stratigraphic sequence that significantly contributed to the formation of clay deposits, which were also influenced by the region's neotectonic activity (Dondi *et al.*, 2025).

The primary stratigraphic units of the Sile area span a broad temporal range from the Ordovician to the Carboniferous periods. The Kurtköy Formation (Lower Ordovician) is a fundamental geological unit of the area, including a sequence of sandstone, conglomerate, and mudstone. The Gözdağ Formation (Upper Ordovician-Lower Silurian) overlies this formation and consists of a sequence of sandstone, shale, and quartzite (Akyüz, 2010). Figure 1 presents the geological map of the area, illustrating the position and distribution of each formation.

The Kartal Formation (Lower Devonian) and the Dolayoba Formation (Upper Silurian to Lower Devonian) superimpose these fundamental units. The Kartal Formation comprises gray and dark gray sandstones, siltstones, and shales, while the Dolayoba Formation is characterized by blue and gray rocks, including limestone. The superjacent Çukurçeşme Formation (Miocene) is distinguished by white, cream, and yellowish clay, sand, and gravel strata (Akyüz, 2010). Clay deposits are notably prevalent in the Çukurçeşme and Kartal Formations (Demir, 2021).

2.1. Formation of Clay Beds

Clay deposits in the Şile area are primarily the result of the physical and chemical weathering of volcanic rocks. Ece and

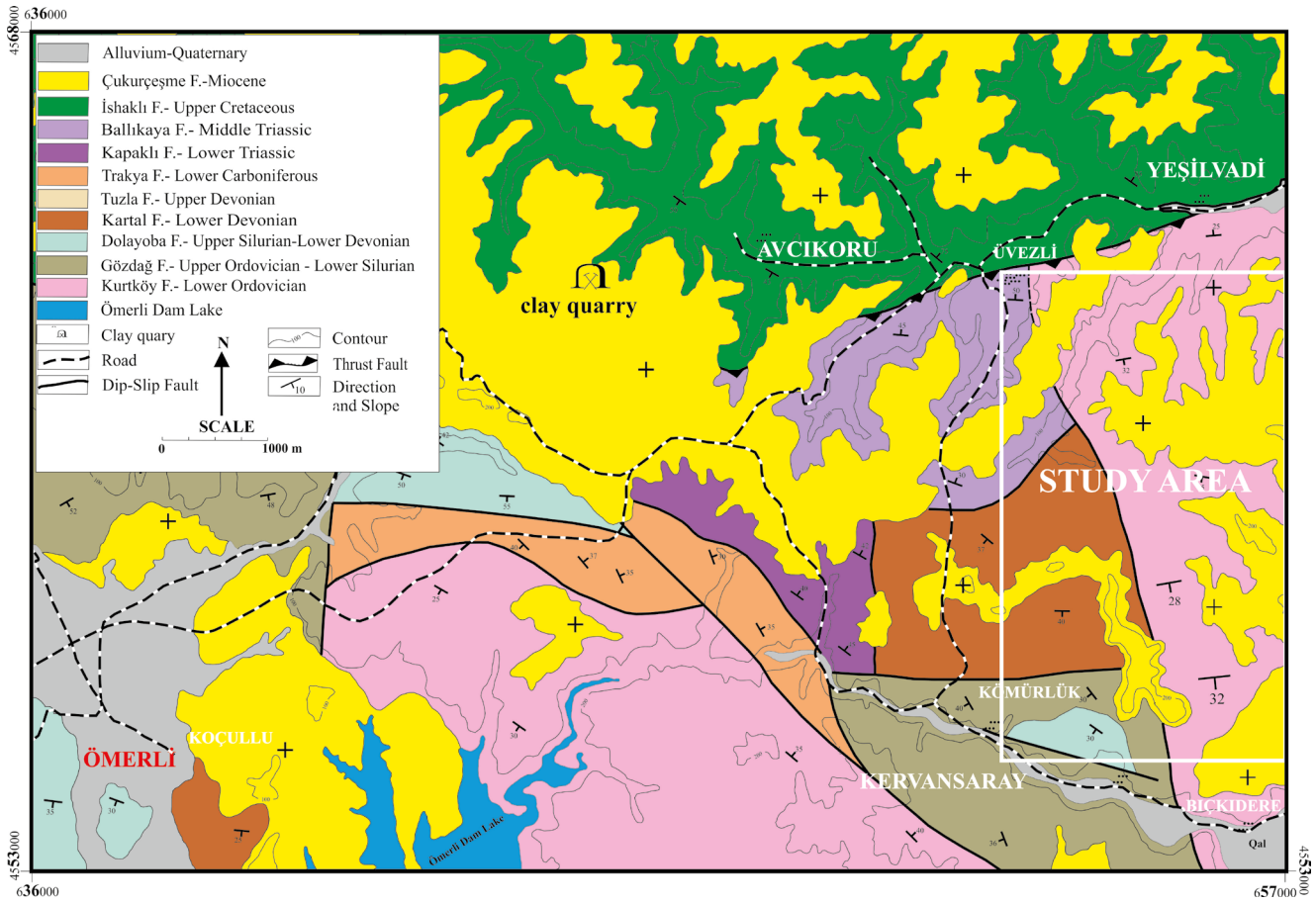


Figure 1. Geology map of the study area (Modified from MTA 1/100 000).

Nakagawa (2003) elucidated the transformation of andesite into kaolinite under low-pH conditions and the effects of organic acids. This approach is crucial for comprehending the mineralogical composition of clays in Şile and their potential for industrial use. Figure 2 displays photographs of these formations, providing a detailed depiction of the primary rock units that constitute the clay deposits.

Clay minerals derived from the weathering of volcanic rocks include kaolinite, illite, and smectite, which are of significant commercial importance (Görhan & Yıldız, 2023).

The presence of these minerals enhances the physical qualities of clay deposits and their industrial significance. The clay deposits of the Çukurçeşme Formation benefit the ceramic industry due to their elevated kaolinite concentration.

2.2. Neotectonic Impacts and Stratigraphic Sequence in the Region

The Şile area lies within an active neotectonic zone of Istanbul, which influences the local rock stratigraphic sequence and erosional processes. The region's fault lines and tectonic processes have shaped the distribution and structure of subsurface clay deposits, guiding their formation (Bozkurtoğlu *et al.*, 2022). Neotectonic activity altered the physical composition of clay deposits, forming clay mineral strata at varying depths. Figure 3 illustrates the locations of the geophysical profiles collected in the research region, thereby enabling thorough mapping of the clay deposits using geophysical techniques.

The geological context is essential for understanding the configuration of the clay deposits in the Şile area and for elucidating the use of geophysical techniques to map them. Research by Akyüz (2010) and Demir (2021) significantly enhances understanding of the geological development of clay deposits by delineating the area's stratigraphic and mineralogical framework.

3. Material and Methods

This research employed a comprehensive near-surface geophysical methodology that integrated Vertical Electrical Sounding (VES) for two-dimensional resistivity modeling and Ground-Penetrating Radar (GPR) to delineate the geometry,

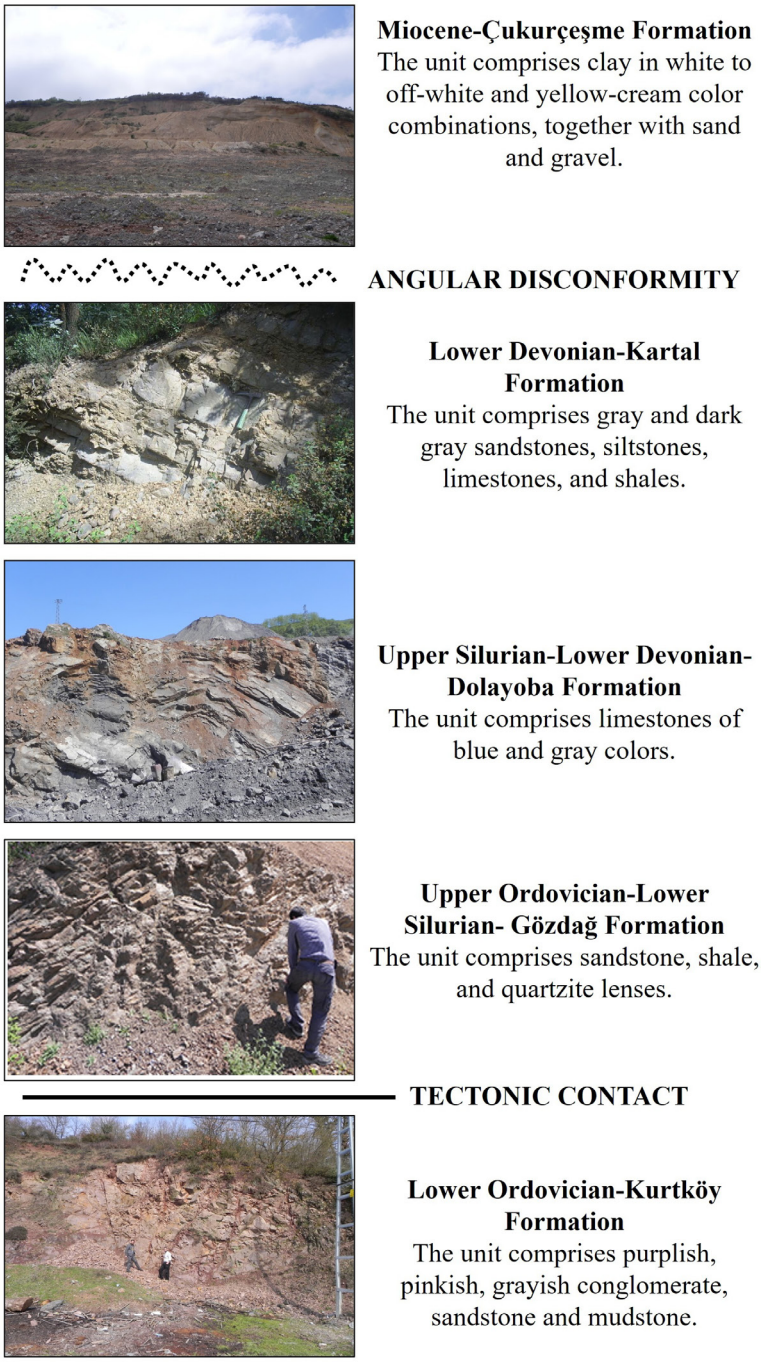


Figure 2. General view of the major rock units in the Şile region.

depth, and internal structure of clay-rich layers within the Çukurçeşme Formation in the Şile region. The integration of electrical and radar methodologies is well-established for enhancing the resolution of subsurface models, especially in heterogeneous sedimentary contexts (Pellicer & Gibson, 2011; Pellicer *et al.*, 2014; Pellicer *et al.*, 2016; Akingboye *et al.*, 2022; Farias *et al.*, 2023; Najaftomraei *et al.*, 2024; Butt *et al.*, 2025). Figure 3 illustrates the spatial distribution and direction of all VES sites and GPR profile lines collected in the study area.

3.1. Electrical Resistivity Sounding (VES) and 2D Modeling

Electrical approaches are exceptionally efficient for identifying conductive subsurface materials, especially water-saturated clay layers, owing to their inherently low resistivity signatures (Loke *et al.*, 2014; Aweto & Mamah, 2014; Riwayat *et al.*, 2018; Loke *et al.*, 2022). While Electrical Resistivity Tomography (ERT) is extensively utilized for 2D and 3D imaging, various studies have shown that VES continues to be a robust and dependable method

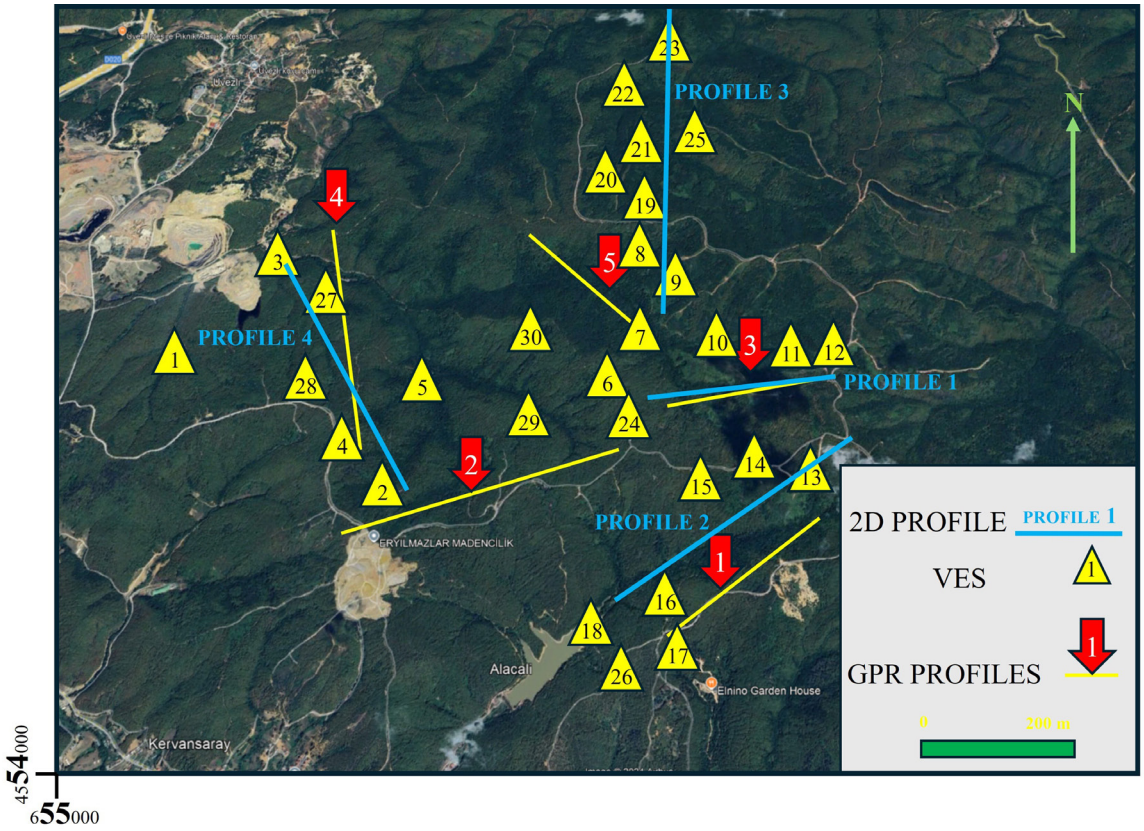


Figure 3. Location map of the study area showing the distribution of VES stations (yellow triangles), GPR profiles (red arrows), and VES profile lines (blue lines). Coordinate system: UTM Zone 35N (WGS84). North arrow and 200-m scale bar are included for reference.

for depth profiling in stratified terrains and for elucidating vertical resistivity variations (Al-Zubedi & Thabit, 2014; Al-Hameedawi & Thabit, 2017; Yalçın, 2025). These attributes render VES especially appropriate for examining the stratified clay-sand-gravel sequences of the Çukurçeşme Formation.

This study collected 30 VES soundings along four survey profiles to assess subsurface lithological changes in the Şile region. All VES measurements were acquired via a digital resistivity meter (SARIS-type instrument) employing a Schlumberger array, selected for its established sensitivity to vertical and lateral resistivity variations in clay-rich environments (Loke *et al.*, 2022). Electrode spacings (AB/2 and MN/2) were progressively increased in logarithmic increments, starting at 1 m and culminating at 120–160 m, contingent upon the available survey area and topographical limitations. This design facilitated research depths of around 35–40 m, aligning with the anticipated thicknesses of clay-rich strata previously documented in the region (Demir, 2021).

To ensure data integrity, each measurement was documented with 3–5 stacks, and values showing voltage drift or instability were repeated. Contact resistances were assessed at each expansion stage, and outliers were removed when variances exceeded 10% of the expected current–voltage relationship. The injection current varied from 20 to 100 mA, automatically calibrated based on subsurface resistivity conditions. All VES stations were georeferenced using handheld GPS devices, and elevation data were integrated into the inversion to rectify the substantial topographic changes observed along the profiles.

The 1D resistivity curves were inverted with IPI2WIN using a mixed smooth-and-layered-earth inversion approach with a maximum of 10 iterations and a target root-mean-square (RMS) misfit of 5–10%. The resulting 1D models were laterally interpolated and correlated to generate quasi-2D resistivity cross-sections, thereby improving the visibility of subsurface continuity between neighboring VES stations. To assess the internal coherence of the models, pseudosections were generated in RES2DINV, incorporating topographic corrections derived from profile-specific elevation data.

The analyzed resistivity sections indicate low-resistivity intervals—generally <50–150 Ω·m—that correspond to clay-dominated, water-saturated regions, consistent with known resistivity ranges for fine-grained, conductive sediments (Loke *et al.*, 2014; Riwayat *et al.*, 2018). The modeled sections provided the basis for identifying deeper clay layers and for incorporat-



Figure 4. Field photographs from the Şile region: (a–c) outcrop views showing clay-rich units of the Çukurçeşme Formation; (d) GPR data acquisition with a 38–50 MHz antenna; (e) VES field setup.

ing the VES-derived structure with shallow GPR reflections collected along the same profiles. Figure 4 illustrates the field circumstances and the VES acquisition configuration.

3.2. Ground Penetrating Radar (GPR)

GPR is a radar imaging technique that delineates near-surface lithological boundaries with high resolution, particularly in dry or moderately saturated sediments (Pellicer & Gibson, 2011; Pellicer *et al.*, 2014, 2016). Nevertheless, fast attenuation may transpire in water-saturated clays owing to elevated electrical conductivity. Notwithstanding this constraint, combining GPR with electrical resistivity methods improves the precision of subsurface mapping (Farias *et al.*, 2023; Drahor & Berge, 2017).

GPR profiles were acquired along five lines throughout the research region using a 38–50 MHz shielded antenna, achieving an optimal balance between penetration depth (approximately 8–10 meters) and horizontal resolution. Parameters for data acquisition included:

- Tracing spacing: 0.25 to 0.5 meters,
- Time interval: 100–150 ns.
- Sampling interval: 0.8–1.0 nanoseconds.
- Implementing multiple stacking per trace to mitigate random noise.

Processing was conducted in Prism 2.5, adhering to a typical protocol that included: (1) dewow filtering, (2) background elimination, (3) gain modifications, (4) band-pass filtering, and (5) Stolt migration.

Velocity estimates necessary for migration (0.06–0.09 m/ns) were derived from hyperbola fits to diffraction patterns. The analyzed radargrams (Figure 5 and Figure 6) clearly show shallow reflectors and stratification; pronounced attenuation zones align with clay layers with elevated water content.

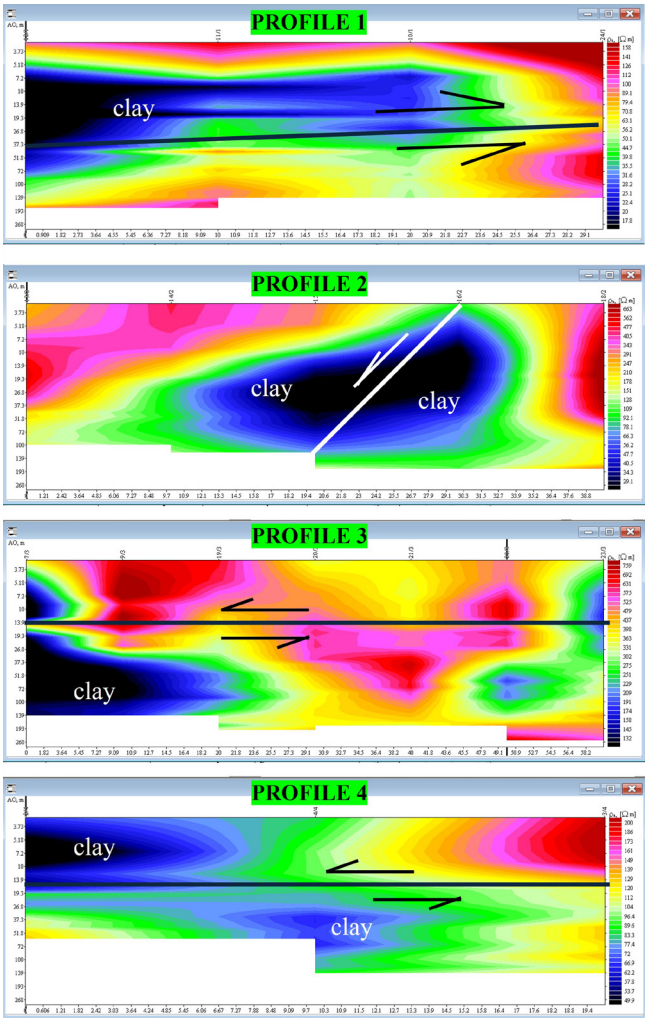


Figure 5. Quasi-2D sections generated from inverted VES data for Profiles 1–4. Resistivity values are shown in ohm-meters. Clay-rich zones correspond to low-resistivity intervals. Vertical axis = depth (m), horizontal axis = distance along profile (m). Coordinate-referenced VES stations are indicated above each section.

3.3. Data Integration and Interpretation

VES-derived resistivity models and GPR radargrams were collaboratively analyzed to generate a cohesive subsurface model of the clay deposits. VES provided reliable data on the depth, thickness, and electrical characteristics of clay-rich strata extending to 60–80 m, while GPR enhanced delineation of the near-surface boundary within the upper 5–10 m. The integration of these methods facilitated the mapping of:

- geometry of the clay layer,
- lateral continuity
- structural disruptions
- zones saturated with water,
- superficial stratification.

The integrated interpretation (Figures 5 and 6) strengthened confidence in the geological limits and yielded a more precise assessment of clay thickness throughout the study region. The integration of electrical and radar-based geophysical techniques complies with international standards for subsurface characterisation of complex sedimentary formations (Farias *et al.*, 2023).

3.4. Topographic Handling of GPR data

The GPR profiles are depicted under the assumption of level topography. Despite the presence of local elevation fluctuations along the survey lines, the relative elevation differences are minimal (about 1–2 m) in comparison to the shallow inquiry depth (often <3–5 m). The primary aim of the GPR interpretation was to delineate stratigraphic boundaries and attenuation zones linked to clay-rich strata, rather than to do structural dip analysis. Consequently, the modest topography differences do not substantially influence the stratigraphic interpretation, and no topographic correction was implemented in the GPR sections.

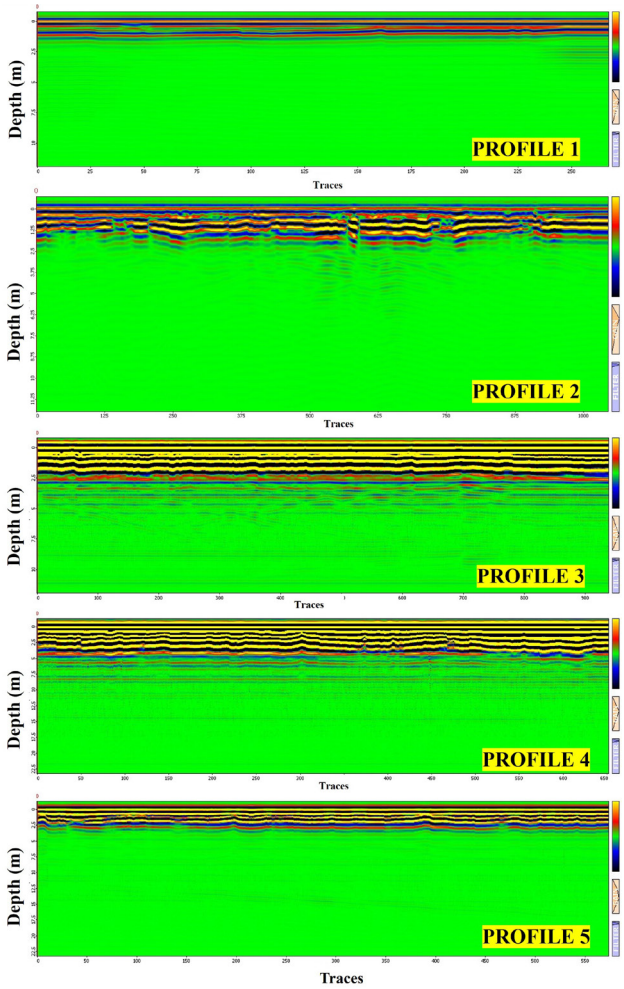


Figure 6. Processed GPR radargrams from Profiles 1–5 showing shallow stratigraphic reflections and attenuation zones associated with clay-rich layers.

4. Results

The VES-derived resistivity sections (Figure 5) indicate laterally continuous low-resistivity zones interpreted as clay-rich and water-saturated strata. The conductive intervals generally span from 50 to 150 Ω·m, aligning with the electrical characteristics of damp clay units reported in prior research (Loke *et al.*, 2022; McKnight & Saneiyan, 2024). The resistivity distribution indicates that clay layers occur at varying depths across the four profiles, with moderate lateral thickness variations.

In Profile 1, the primary clay stratum commences at a depth of around 5–8 m and extends to 18–22 m, with an average thickness of 12–14 m. Profile 2 features a less deep yet somewhat thicker clay layer, with its upper border situated at 4–6 m and a maximum thickness approaching 15 m. Profile 3 displays a notable clay horizon at 6–10 m, underpinned by a distinctly higher-resistivity layer. In Profile 4, clay units are distributed discontinuously, exhibiting localized thickening in the middle region of the line. The quantitative thickness estimates obtained from VES interpretations are compiled in Table 1, which consolidates top, bottom, and estimated thickness values for each profile.

The VES data delineate the fundamental geometry of the deeper clay-rich strata and illustrate the heterogeneity of the Çukurçeşme Formation. These conclusions are consistent with previous observations that clay layers in mixed sand–gravel–clay sequences generally exhibit high conductivity (Akingboye *et al.*, 2024).

Complementary GPR radargrams obtained along five profiles (Figure 6) offer high-resolution imaging of the shallow subsurface. The upper limits of the clay strata align with continuous or semi-continuous reflectors, below which there is a swift decline in signal strength attributable to elevated water content and the inherent conductivity of clay materials (Pellicer & Gibson, 2011). Significant attenuation in Profiles 1 and 2 suggests the presence of a superficial, water-saturated clay layer, consistent with the VES results.

Table 1. Calculated depths and thicknesses of clay horizons inferred from resistivity sections obtained by VES analysis.

Profile	Clay top depth (m)	Clay bottom depth (m)	Thickness range (m)	Notes
P1 (NE–SW)	~10–12	~30–38	~18–26	Laterally continuous low-resistivity band
P2 (NE–SW)	~8–12	~35–42	~23–30	Thick conductive zone, locally >30 m
P3 (S–N)	~5–10	~25–35	~15–25	The clay horizon shallows towards the south
P4 (SE–NW)	~3–8	~20–30	~12–22	Upper clay body; local deeper pocket to ~35 m

In Profile 3, the base of the primary clay layer is identifiable at a depth of roughly 7–8 m, aligning with the resistivity-derived base of the same unit. In this horizon, distinct, elevated reflections indicate sand-dominated layers with higher resistivity. Comparable stratigraphic correlations are evident in Profiles 4 and 5, although GPR penetration diminishes as clay content and saturation rise.

The GPR data accurately outline the upper limits, internal stratification, and superficial structural changes of the clay strata. This near-surface resolution enhances the penetration depth achieved by VES.

The integrated analysis of VES and GPR data yields a more consistent and reliable subsurface model of the clay-dominated strata in the Şile region. VES delineates the intricate geometry, thickness, and lateral continuity of clay strata, whereas GPR enables the identification of surface boundaries and internal stratification.

Strong agreement is evident between the two datasets, particularly in Profile 1, where the low-resistivity zones from VES correspond closely to high-attenuation regions in the radargrams. This cross-validation enhances confidence in the inferred clay boundaries and underlines the susceptibility of both approaches to moisture-rich fine-grained sediments (Farias *et al.*, 2023).

The integrated results highlight the following significant characteristics:

- Clay strata are laterally continuous but display significant thickness differences across profiles.
- Water-saturated zones greatly influence both resistivity and radar attenuation.
- Shallow reflectors captured by GPR align with the upper limits of low-resistivity strata identified by VES.
- The subsurface architecture of the clay-rich strata is diverse, indicating the depositional nature of the Çukurçeşme Formation.

The results delineate the geometry, continuity, and moisture content of clay deposits in the Şile region, furnishing essential insights for assessing their economic viability and establishing a scientific framework for analogous geological contexts.

5. Discussion

The present study revealed that the synergistic use of Vertical Electrical Sounding (VES) and Ground-Penetrating Radar (GPR) is highly effective at distinguishing the geometry, depth, and structural attributes of clay-rich layers within the Çukurçeşme Formation. The findings demonstrate that combining electrical and electromagnetic techniques yields a more comprehensive understanding of subsurface conditions than applying each method separately, consistent with global research (Loke *et al.*, 2022; Alao *et al.*, 2024).

Recent research highlights that resistivity-based techniques are especially effective for detecting water-saturated clay layers due to their characteristic low-resistivity signatures (Loke *et al.*, 2014; Riwayat *et al.*, 2018; Loke *et al.*, 2022). While numerous studies employ Electrical Resistivity Tomography (ERT), research by Al-Zubedi and Thabit (2014), Al-Hameedawi and Thabit (2017), and Yalçın (2025) underscores that VES remains an effective technique for depth profiling in stratigraphically complex settings. The current study validates this, as VES effectively identified the deeper clay-rich strata and associated vertical resistivity changes throughout the Şile region.

Similar findings have been documented in Brazil, where Farias *et al.* (2023) showed that combining resistivity techniques with GPR enhances the delineation of moisture conditions and the internal structure of clay layers. Their findings emphasize that integrated geophysical techniques improve structure analysis in intricate sedimentary settings. The integration in Şile improved the definition of clay boundaries, facilitating a more precise understanding of both deep and shallow subsurface geometries (Dondi *et al.*, 2025).

Similar studies in Turkey (Kurtuluş *et al.*, 2009; Yılmaz *et al.*, 2019; Balkaya *et al.*, 2021; Karslı *et al.*, 2024; Yalçın, 2025; Yalcin, 2026) further substantiate the assertion that electrical and radar-based geophysical methods are mutually reinforcing. Drahor (2011) observed that the synergistic employment of resistivity techniques with ground-penetrating radar is very effective for delineating water-saturated clayey formations in western Turkey. The current findings corroborate these results, indicating that GPR yields precise shallow reflections, albeit with a limited penetration depth in highly conductive, clay-rich areas. This constraint is well documented in the literature, indicating that water-saturated clays consistently exhibit significant GPR attenuation (Pellicer & Gibson, 2011; Najaftomraei *et al.*, 2024).

Akingboye (2024) reported in concurrent studies from Nigeria that combining electrical and radar data markedly enhances the accuracy of subsurface clay identification. The present findings corroborate this conclusion: in the Şile profiles, areas of significant GPR attenuation closely align with the low-resistivity clay strata identified in VES models, thereby strengthening the validity of the interpretations (Pellicer & Gibson, 2011).

Geological activities additionally influence the distribution of clay in Şile. Neotectonic activity and erosional processes have significantly contributed to the exposure and redistribution of clay-rich sediments in the region (Akyüz, 2010; Ece & Nakagawa, 2003). These structural and geomorphological elements may change moisture content and resistivity conditions, hence impacting geophysical responses.

This study's findings corroborate previous conclusions that integrating resistivity and radar techniques improves the precision of subsurface models, particularly in diverse formations where single-method approaches may be inadequate (Alao *et al.*, 2024). In Şile, VES provided reliable data on deeper strata, while GPR provided comprehensive imaging of near-surface reflectors. Collectively, these findings enhance clarity in interpreting the geometry and continuity of clay deposits.

Ultimately, while the integrated VES–GPR methodology has demonstrated efficacy, supplementary geophysical techniques could further enhance understanding of subsurface clay structures. Future investigations could integrate techniques such as Induced Polarization (IP) or Magnetotellurics (MT) to improve sensitivity for describing mineralogical variability, subsurface structures, and clay-bound water content.

This study demonstrates that the combined use of electrical and radar geophysical data provides a reliable and comprehensive framework for delineating clay-rich layers in geologically complex regions such as Şile.

6. Conclusion

This work revealed that the combined application of VES and GPR is exceptionally successful for defining the geometry, depth, and structural attributes of clay-rich layers within the Çukurçeşme Formation in the Şile region. The VES results accurately revealed deeper low-resistivity, moisture-laden clay strata, whereas GPR offered high-resolution imaging of near-surface interfaces and interior stratification. The integration of these complementary datasets yielded a cohesive subsurface model that would not have been attainable using either method independently.

The integrated interpretation indicated that the clay strata in the research area are laterally continuous but exhibit varying thicknesses, influenced by local stratigraphic transitions and moisture conditions. Shallow attenuation zones in the GPR radargrams closely correlate with conductive intervals in the VES models, hence affirming the existence of water-saturated clay layers. These findings corroborate prior research highlighting the susceptibility of electrical and radar techniques to fine-grained, high-moisture substances.

The geological and neotectonic processes in the Şile region have facilitated the preservation and near-surface exposure of clay deposits, underscoring their economic significance. This work offers significant insights into the distribution and thickness of these deposits; nonetheless, the findings should be interpreted as a structural and geophysical characterization rather than a comprehensive economic evaluation.

This work demonstrates the effective use of integrated VES and GPR technologies for mapping clay-bearing strata in heterogeneous sedimentary environments. The provided interpretative framework may serve as a reference for future research in analogous geological contexts. Supplementary geophysical methods—such as IP or MT—may enhance the comprehension of mineralogical variability and deeper structural characteristics in future investigations.

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8. Declaration of Competing Interest

Conflict of interest: The authors declare they have no competing interests.

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No funding.

10. Authorshhip

Cihan YALÇIN includes fieldwork, geology, mapping, data analysis and interpretation, manuscript drafting, and critical revision. Hurşit Canli field work, geophysics measurements, data curation, and preparation. Mustafa Kumral fieldwork, geology, Mustafa Kaya fieldwork, data interpretation, Sercan Öztürk fieldwork, and data curation. The authors read and approved the manuscript.

Availability of data and materials: This published article includes all data generated or analyzed during this study.

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