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GEOCIENCES

Comparison of geophysical survey and diamond core drilling results in a potential basalt quarry site

Adil Ozdemir[1*] and Alperen Sahinoglu[2]

[1]Department of Geological Engineering, Institute of Science and Technology, Ataturk University, Erzurum, Turkiye. [2]Technical Sciences Vocational School, Niğde Ömer Halisdemir University, Niğde, Turkiye. *Author for correspondence. E-mail: adilozdemir2000@yahoo.com

ABSTRACT. This study evaluated the suitability of a potential site for quarrying. Geoscientific data are needed to assess the potential of a site for quarrying. These geoscientific data are geological, geophysical, and drilling data. Diamond core drilling boreholes are drilled at 23 - 35 m depths in the study area. According to the diamond core drilling results, the site was not considered suitable for quarrying due to the very low core recovery of the basalts. For this reason, geophysical measurements were carried out to compare the relationship between core recoveries and resistivity values of the boreholes drilled in the study area. Resistivity measurements were made with the vertical electrical sounding (VES) methodat the exact coordinates of 5 boreholes in the study area, which have different characteristics according to the core recovery data. Resistivity measurements showed very low resistivity values, which may belong to altered basalts instead of strength basalt-type rocks. The results obtained were also checked with gravity and magnetic maps. The results of drilling and geophysical investigations were found to be entirely compatible. Thus, while the suitability of the drilling results in the study area was confirmed, it was also concluded that the suitability of a potential site for quarrying could be reliably evaluated with resistivity measurements, gravity, and magnetic data. This study demonstrates that geophysical methods (especially resistivity) can be fast, reliable, and cost-effective methods for quarry site research.

Keywords: quarry site; crushed stone; resistivity; vertical electrical sounding (VES); geophysical modelling; rock quality designation (RQD).

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Introduction

Due to quarrying, projects' ballast and other construction materials are produced from suitable sites. In this context, after initially assessing the suitability of both the technological and physical properties of rocks in regions selected as quarry sites for the required construction materials, the thickness and extent of the rock in potential sites become critical. Geophysical methods are the fastest and most cost-effective way to determine these factors. The main reason for choosing geophysical methods is that potential quarry sites often lack infrastructure (such as roads), and there is no need for permissions from authorized institutions for drilling. Geophysical methods are also used for site development in quarries that are already operational. Some preliminary studies in the literature on this topic are as follows;

Yi et al. (2006) developed a three-dimensional (3D) resistivity inverse resolution algorithm for resistivity tomography. Their study, which included resolution analysis through numerical simulations, demonstrated that 3D resistivity tomography has excellent potential for creating detailed 3D images of the subsurface. The study highlighted the importance of considering topographic effects in the inverse solution to achieve accurate 3D subsurface imaging. Additionally, this method successfully identified faults or fractures in a granite quarry.

Chambers et al. (2006) employed 2D and 3D electrical resistivity tomography to define the geometry of an old dolerite quarry and a buried quarry underneath a landfill. They also mapped the dolerite contamination from the landfill and characterized the site's geological features. The combined 3D analysis of electrical resistivity tomography with conventional field survey data proved an exceptionally effective technique for characterizing the landfill and its environment. The 3D resistivity model effectively confirmed the landfill boundaries, which were distinctly defined and closely matched historical maps and field survey data. Moreover, the electrical models revealed a potential leachate migration zone from the landfill, aligning with the predicted groundwater flow direction across the site. High resistivity sheet-like features indicated intact sections of dolerite sill, while low resistivity values identified the fault zone in the 2D resistivity model.

Agunleti & Jaiyeola (2015) performed a geophysical survey and assessment of a potential dolerite quarry site using the Vertical Electrical Sounding (VES) method. Their findings suggested that the site might not be economically viable for quarrying, as the cover layer's thickness over the dolerite dyke, which is buried within the sedimentary units, was found to range between 60 and 70 meters.

Uhlemann et al. (2018) used electrical resistivity tomography in an ornamental quarry currently in operation. They reported that geophysical measurements can be suitable for obtaining information about stone properties before extracting ornamental stone. They also stated that it would help to guide quarry operation processes and allow for the conscious, safe, and efficient extraction of high-quality stone, thus increasing sustainability and economic competitiveness.

Kayode et al. (2019) used electrical resistivity tomography to determine the granitic mass depth and the regolith thickness covering the granite unit in a potential quarry where construction material could be obtained. The depth of the granite unit was found to vary between 5-100 m, and the resistivity values recorded were more outstanding than 6000 Ω-m in most of the profiles. According to these results, the thickness and distribution of the granitic rock unit studied are suitable for quarrying. In addition, groundwater-bearing sites were identified within the granite unit.

Martial et al. (2023) conducted a research and evaluation study to determine and estimate the exploitable granite quantity in a potential granitoid quarry area based on electrical resistivity methods. In the study, both VES and 2D tomography measurements were used together to create a 3D subsurface model of the study area, and a reserve calculation for granitoid was made based on the 3D model created according to the geophysical measurement data.

The study area is located within the borders of the Emirdağ district of Afyon province (Figure 1). The Karaçaltepe Limestone Member of the Middle-Upper Triassic Emirdağ Group is the older unit, and the Karakaya Basalt of the Pliocene Gebelciler Formation is the younger unit (Figure 2).

Figure 1. Location map of the potential quarry site.

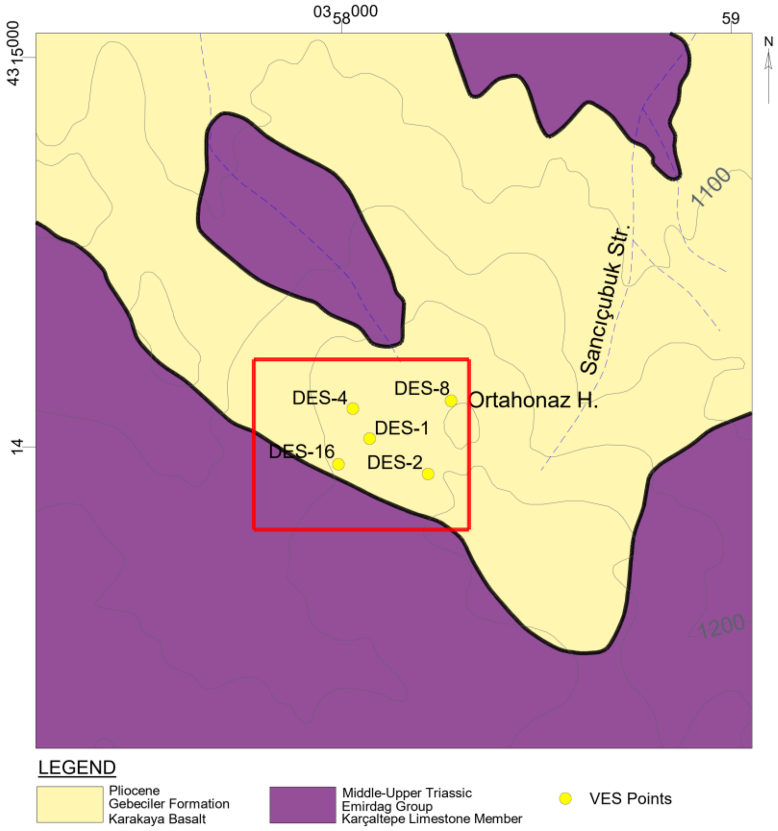


Figure 2. Geological map of the potential quarry site.

The primary purpose of diamond core drilling is to obtain information about the subsurface geology by taking cylindrical samples called cores from the drilled geological formations (Cumming, 1980; Heinz, 1985; Hilliard, 1996). Geological interpretations and geotechnical assessments of these drill cores, which represent the geological units in the subsurface, and laboratory tests to be carried out on the samples are used to assess the site's suitability for quarrying and, if suitable, its reserve estimation. In the study area, 13 diamond core drilling boreholes were drilled at 23 - 35 m depths. According to the drilling results, the area was not considered suitable for quarrying due to the very low core recovery of the basalts. For this reason, geophysical measurements were carried out to compare the relationship between core recoveries and resistivity values of the boreholes drilled in the study area. Resistivity measurements were made with the VES method at the same coordinates as 5 boreholes in the study area, which have different characteristics according to the core data. The results obtained were also checked with gravity and magnetic maps.

Material and method

The resistivity method operates by leveraging the variations in electrical resistance within the environment. It involves measuring the potential difference in the field on the earth's surface, with an electric current introduced between two points, and analyzing the results based on Ohm's law (Figure 3).

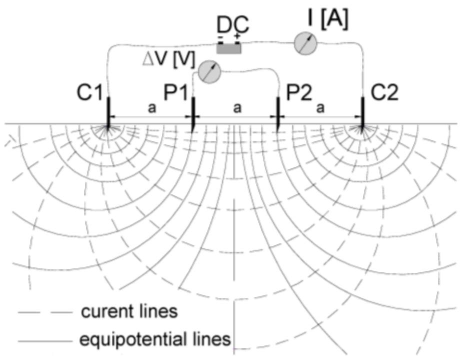


Figure 3. Field application of resistivity method.

Geological units in the study area are considered when evaluating VES measurements. The geoelectrical structure is compared with these units. In this way, the geological structure is indirectly determined. The geological structure may not always match the geoelectrical structure exactly. However, this method identifies the subsurface by comparing the detected high-resistivity (resistive) and low-resistivity (conductive) environments with the geological structure. Evaluating geophysical data and geological observation is an inevitable practice for the decisions to be made in the future drilling and project design stages in light of geophysical measurements (Özdemir & Savaş, 2009).

Within the scope of this study, firstly, regional gravity and airborne magnetic data were obtained from the General Directorate of Mineral Research and Exploration of Turkey (MTA) to estimate the presence, thickness, and vertical and lateral distribution of basalt in the sites selected as quarries by geophysical methods, and maps were prepared and interpreted using Surfer software. In the second stage, geological observations were made, and geological maps were prepared using the NetCAD software to examine the geological characteristics and guide the geophysical measurements in these sites. In the third stage, geoelectrical measurements were carried out to estimate basalt's presence, thickness, and distribution in the selected quarry sites by resistivity methods.

Geoelectrical field measurements were conducted using resistivity equipment with a 3-amp capacity (GeoScanner 1-2 AH model). The system's power source was a gasoline generator with an alternating current (AC) of 220 volts and 5.5 kW. The receiver's sensitivity was calibrated to 0.01 mV/scala. Within the setup, the alternating current generated by the power source was first regulated using a variac before being converted to direct current (DC) via a rectifier. This DC was then transmitted to the subsurface. The output voltage for the DC reached up to 1000 volts, with a maximum subsurface current of 2 amps. Stainless steel rods served as the current electrodes (C1, C2), while non-polarized copper sulfate electrodes were used as potential electrodes. All cables used were made of copper and were well-insulated. Since the purpose of geoelectrical measurements in the study area is to investigate the changes of geological units in depth, the Schlumberger electrode array was used in VES measurements (Figure 4).

Today, the raw resistivity values collected in the field can be digitized and modeled in 3D. The raw resistivity data and field coordinates are input into software to create a three-dimensional model during this process. This model is converted into a solid form using grid modeling techniques and geostatistical methods. To better interpret the curves and evaluation results obtained from VES measurements, geoelectrical sections, and 3D models were prepared in the RockWorks software following the geological structure to analyze the geoelectrical structure better. Finally, it assessed whether the site was suitable for a quarry, and the geophysical data obtained were compared with diamond core drilling data.

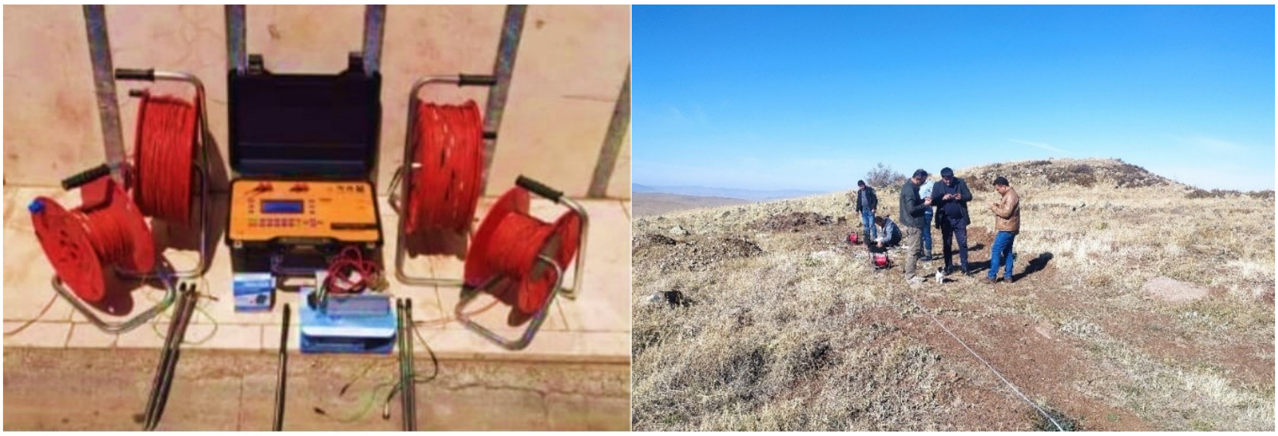


Figure 4. A view of the device used in the geophysical resistivity study and the measurements.

Results and discussion

The first stage of the study involved preparing and interpreting gravity and magnetic maps. Then, 1D, 2D, and 3D geoelectrical curves, cross-sections, and models of the data obtained from resistivity measurements performed in the study area were prepared to evaluate the suitability of the potential quarry site. The results were compared with diamond core drilling data.

Aeromagnetic and gravity data

Typically, dark shades in the gravity contour map indicate younger, low-density rocks, whereas lighter shades signify older, high-density rocks. Interpreting airborne magnetic data and geological modeling of the structures responsible for anomalies involves techniques such as pole reduction and delineation of the approximate boundaries of the geological structure in question, followed by 2D geological modeling of the airborne magnetic data.

Massive basalt formations typically exhibit high magnetic and gravity values. In the gravity map created for this study, the site designated for quarry construction materials is situated within a region of low-density rocks (altered basalt), depicted by dark blue, light blue, and green tones. In contrast, high-density rocks are shown in yellow and red tones (Figure 5). Geological observations revealed that altered basalts are present on the site's surface. Therefore, the reason for the low gravity in the gravity map for the whole site is that the altered basalts continue to a considerable depth. This data is supported by the magnetic map prepared for the study area (Figure 6).

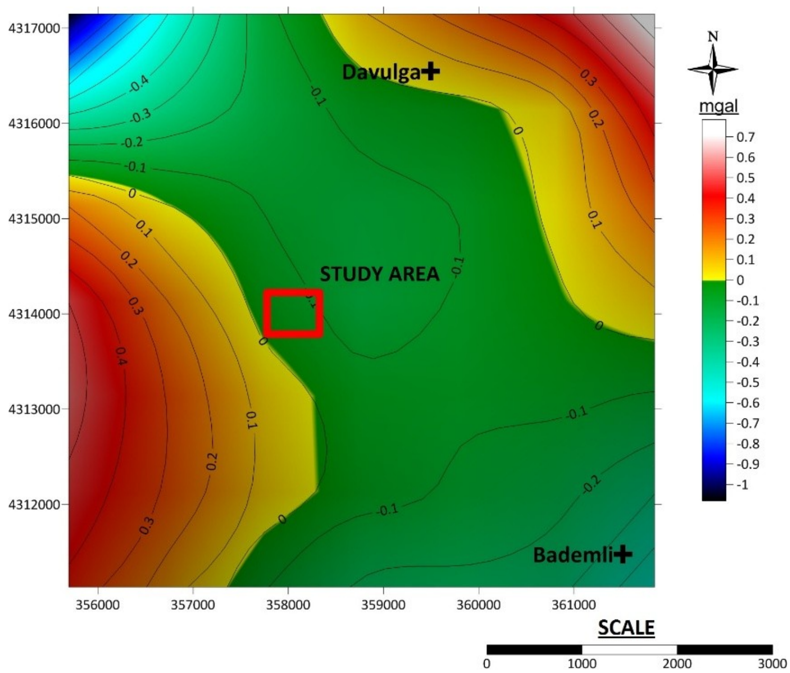


Figure 5. Color contour map of residual gravity anomalies in and around the study area.

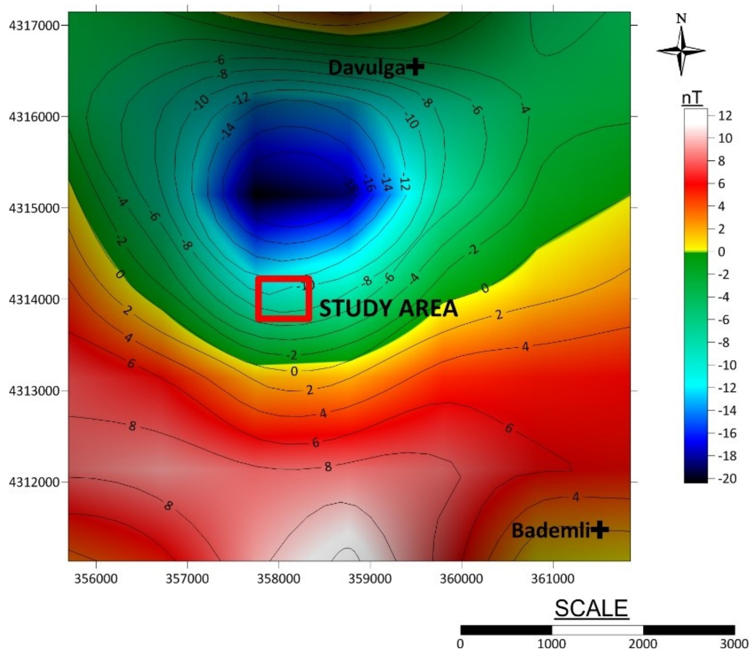


Figure 6. Color contour map of residual aeromagnetic anomalies in and around the study area.

In the magnetic map generated for this study, regions with rocks lacking magnetization (entirely sedimentary in origin) and those with low magnetization (altered basalts) are shown in dark blue, light blue, and green tones. Other areas, particularly those with basalts containing magnetic minerals like magnetite, ilmenite, and pyrrhotite, are represented by yellow, red, and white tones. The distinction between fundamental, ultrabasic, ophiolitic, and volcanic rocks and rocks other than these is revealed in the airborne magnetic color contour map. If the altered basalts in the study area were found only in the surface parts and massive basalts in the lower parts, the study area would be expected to give high magnetic values in the prepared magnetic map. Therefore, the potential quarry site is not considered suitable for basalt supply according to the gravity and magnetic properties it exhibits (Figure 6).

1D geoelectrical model

13 diamond core drilling boreholes were previously drilled at 23-35 m depths in the study area. In this study, resistivity measurements were made at the same coordinate AB/2 = 40 m with 5 boreholes with different characteristics to compare the relationship between the previously drilled boreholes' core recoveries and resistivity values. The locations of the measured VES points in the study area are given in Table 1 and Figure 7.

Table 1. Coordinates of VES measurements measured in the study area.

Measurement No.	Coordinates	
	Y	X
DES-1	358072	4314022
DES-2	358222	4313931
DES-4	358029	4314099
DES-8	358281	4314119
DES-16	357992	4313956

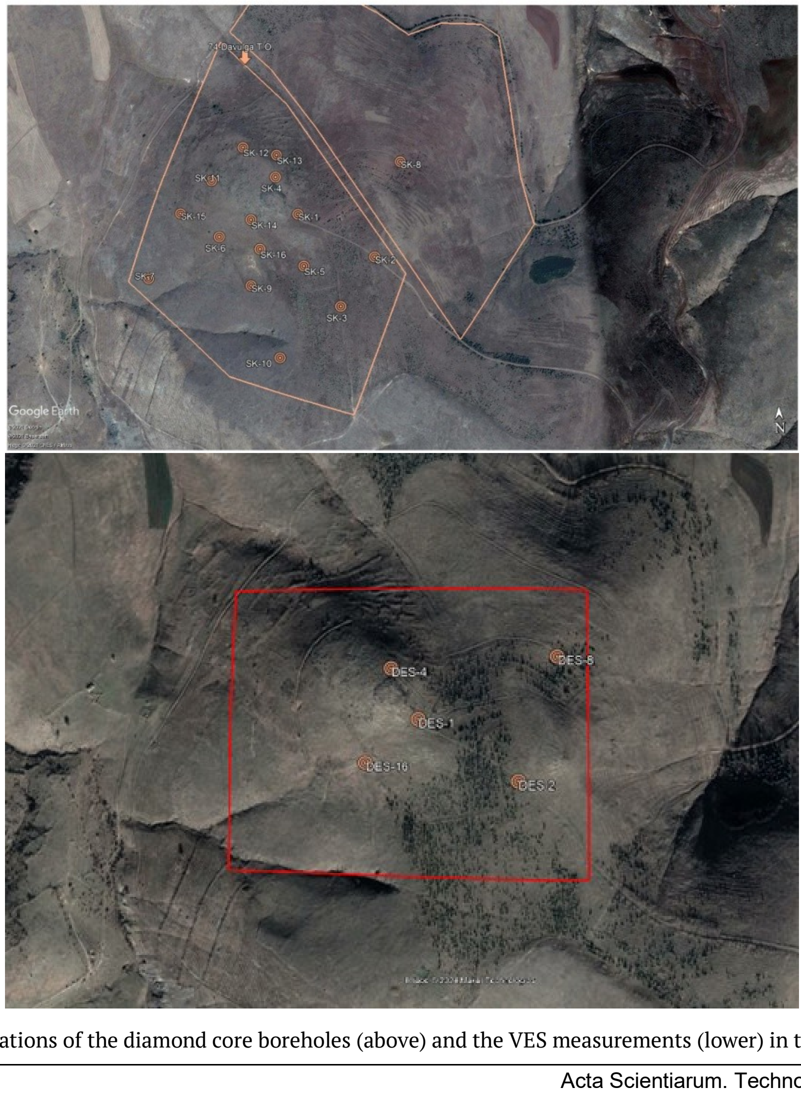
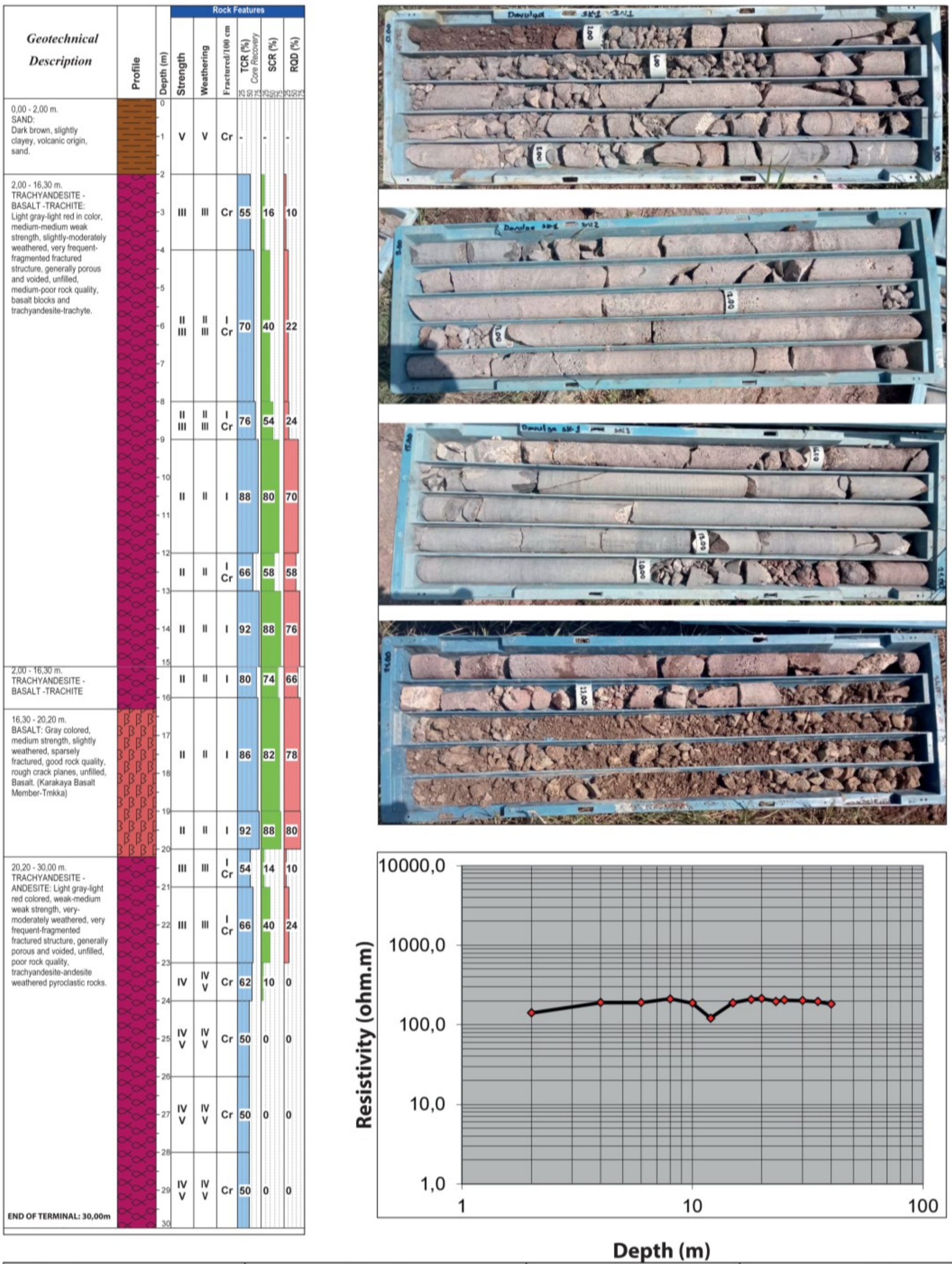


Figure 7. Locations of the diamond core boreholes (above) and the VES measurements (lower) in the study area.

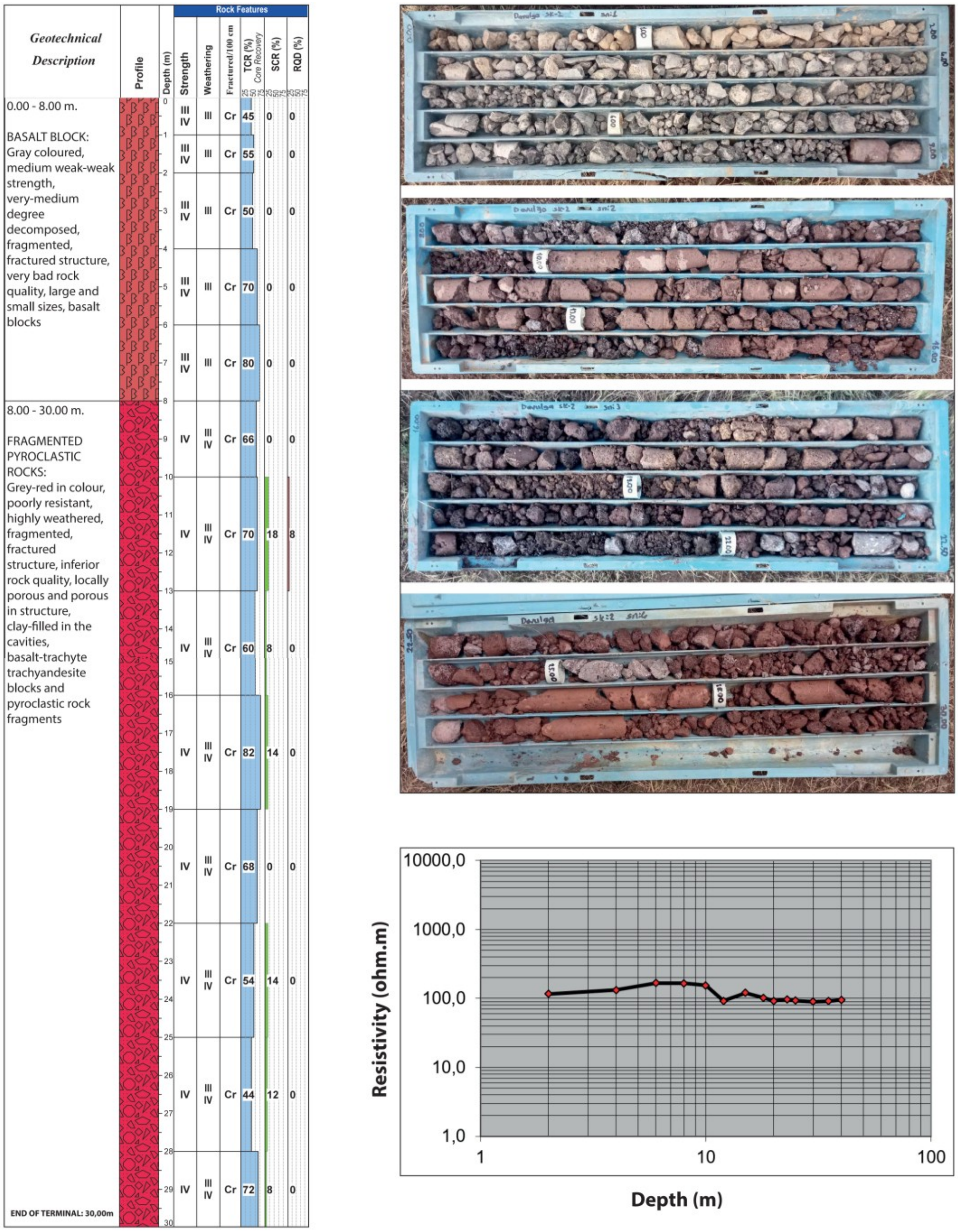
Rock quality designation (RQD) is a reliable rock mass quality parameter commonly obtained in subsurface investigations (Gemail et al., 2020; Hasan et al., 2023; Junaid et al., 2024). The core recovery (RQD) of borehole SK-1 is in the range of 0-76% (RQD = > 10 cm core recovery) (Figure 8). In the first 9 m, it is 0-24%. These core recoveries are pretty low. According to the borehole log, the first 9 m is defined as altered basalt. Between 9-30 m is characterized as partially good rock quality. In the DES-1 (borehole SK-1 location) measurement (Figure 8), resistivity values of 121.1-213.2 ohm.m were measured. These values are pretty low for massive basalt-type rocks. Therefore, based on geological field observations, it was evaluated that altered basalts are present at the DES-1 measurement location.



Weathering		Strength		1 m Fractures	RQD	
W1	*Fresh*	V	*Very Weak*	< 1 Wide (W)	%0-25	*Very Poor*
W2	*Slightly W.*	IV	*Weak*	1-2 Moderate (M)	%25-50	*Poor*
W3	*Moderatly W.*	III	*Moderatly Weak*	3-10 Close (Cl)	%50-75	*Fair*
W4	*Highly W.*	II	*Moderatly Strong*	10-20 Intense (I)	%75-90	*Good*
W5	*Completely W.*	I	*Strong*	>20 Crushed (Cr)	%90-100	*Excellent*

Figure 8. Comparison of DES-1 measurement curve (borehole SK-1 location) and diamond core drilling results (borehole log and the views of core boxes).

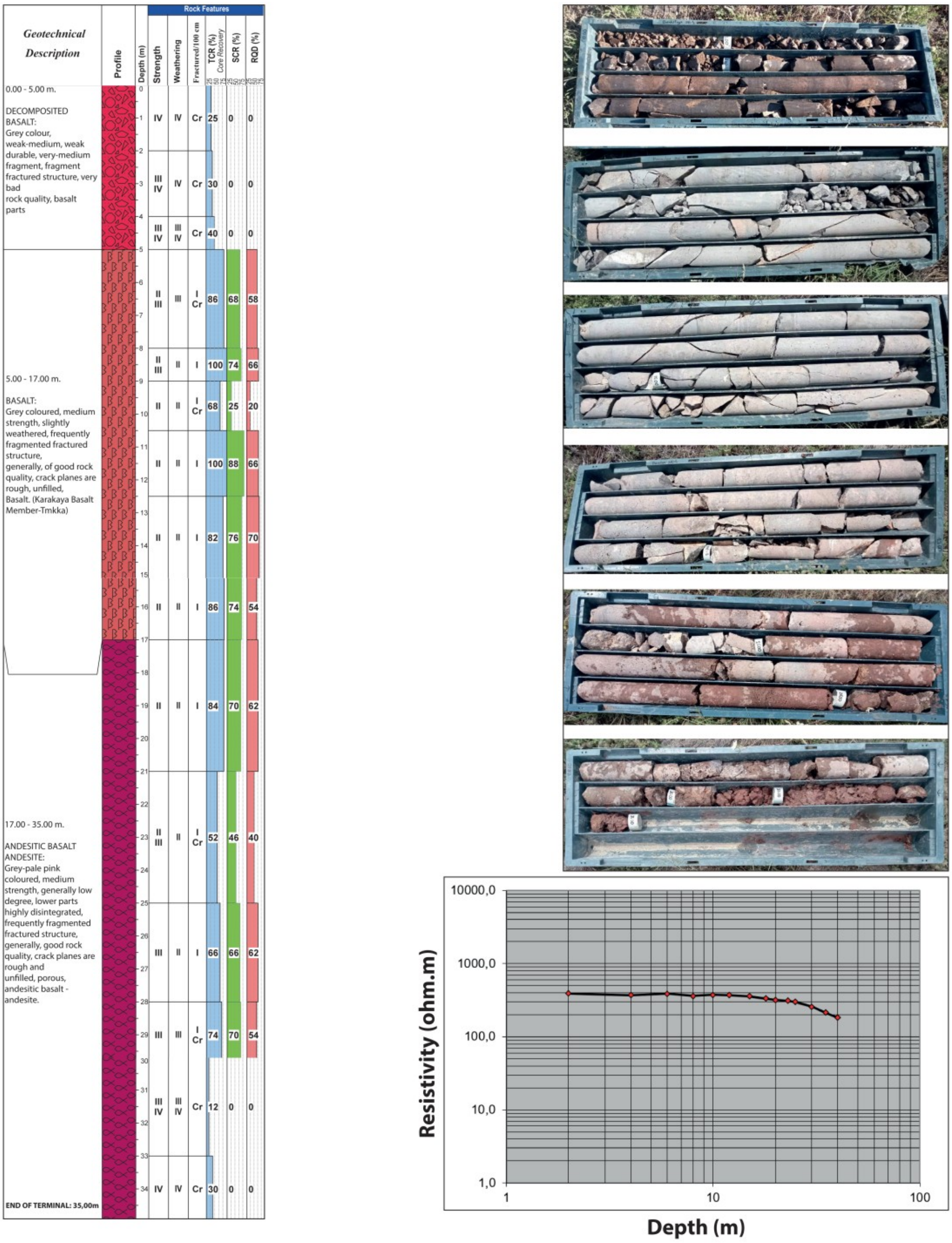
The RQD of borehole SK-2 is 0% (Figure 9). According to the borehole log and core box photography, basalt is completely altered. In the DES-2 (borehole SK-2 location) measurement (Figure 9), resistivity values of 89.5-166.6 ohm.m were measured. These values are pretty low for basalt-type rocks. Therefore, based on geological observations, it can be evaluated that altered basalts are present at the DES-2 measurement location.



Weathering		Strength		1 m Fractures	RQD	
W1	*Fresh*	V	*Very Weak*	< 1 Wide (W)	%0-25	*Very Poor*
W2	*Slightly W.*	IV	*Weak*	1-2 Moderate (M)	%25-50	*Poor*
W3	*Moderatly W.*	III	*Moderatly Weak*	3-10 Close (Cl)	%50-75	*Fair*
W4	*Highly W.*	II	*Moderatly Strong*	10-20 Intense (I)	%75-90	*Good*
W5	*Completely W.*	I	*Strong*	>20 Crushed (Cr)	%90-100	*Excellent*

Figure 9. Comparison of DES-2 measurement curve (borehole SK-2 location) and diamond core drilling results (borehole log and the views of core boxes).

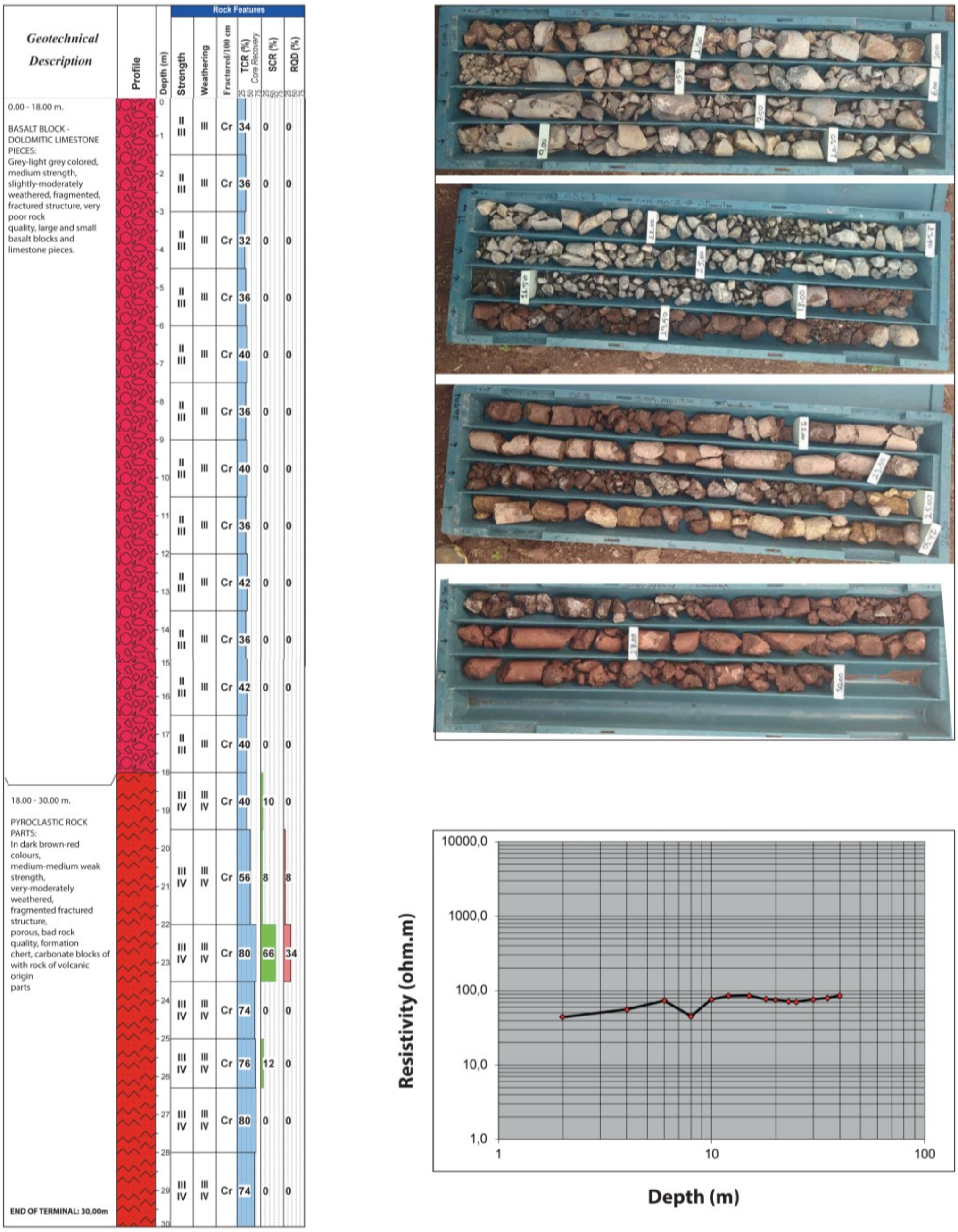
The RQD of borehole SK-4 is 0-70% (Figure 10). In the first 5 m, it is 0. The core recovery is generally good at other depths. According to the borehole log, the first 5 m can be defined as altered basalt. After 5 m, it presents partly good to good rock quality characteristics. In the DES-4 (borehole SK-4 location) measurement (Figure 10), 181.8-390.9 ohm.m resistivity values were measured. These resistivity values are the highest in the 5 locations measured in the study area. Therefore, based on geologic observations, it was evaluated that the DES-4 measurement location contains altered basalts in the upper and partially altered basalts in the lower zones.



Weathering	Strength	1 m Fractures	RQD
W1 *Fresh*	V *Very Weak*	< 1 Wide (W)	%0-25 *Very Poor*
W2 *Slightly W.*	IV *Weak*	1-2 Moderate (M)	%25-50 *Poor*
W3 *Moderatly W.*	III *Moderatly Weak*	3-10 Close (Cl)	%50-75 *Fair*
W4 *Highly W.*	II *Moderatly Strong*	10-20 Intense (I)	%75-90 *Good*
W5 *Completely W.*	I *Strong*	>20 Crushed (Cr)	%90-100 *Excellent*

Figure 10. Comparison of DES-4 measurement curve (borehole SK-4 location) and diamond core drilling results (borehole log and the views of core boxes).

The RQD of borehole SK-8 is close to 0% (Figure 11). According to the borehole log and core box photography, basalt is completely altered. In the DES-8 (borehole SK-8 location) measurement (Figure 11), resistivity values of 44.0-85.6 ohm.m were measured. These values are pretty low for basalt-type rocks. Therefore, based on geologic observations, it can be evaluated that the DES-8 measurement location contains highly altered basalts.

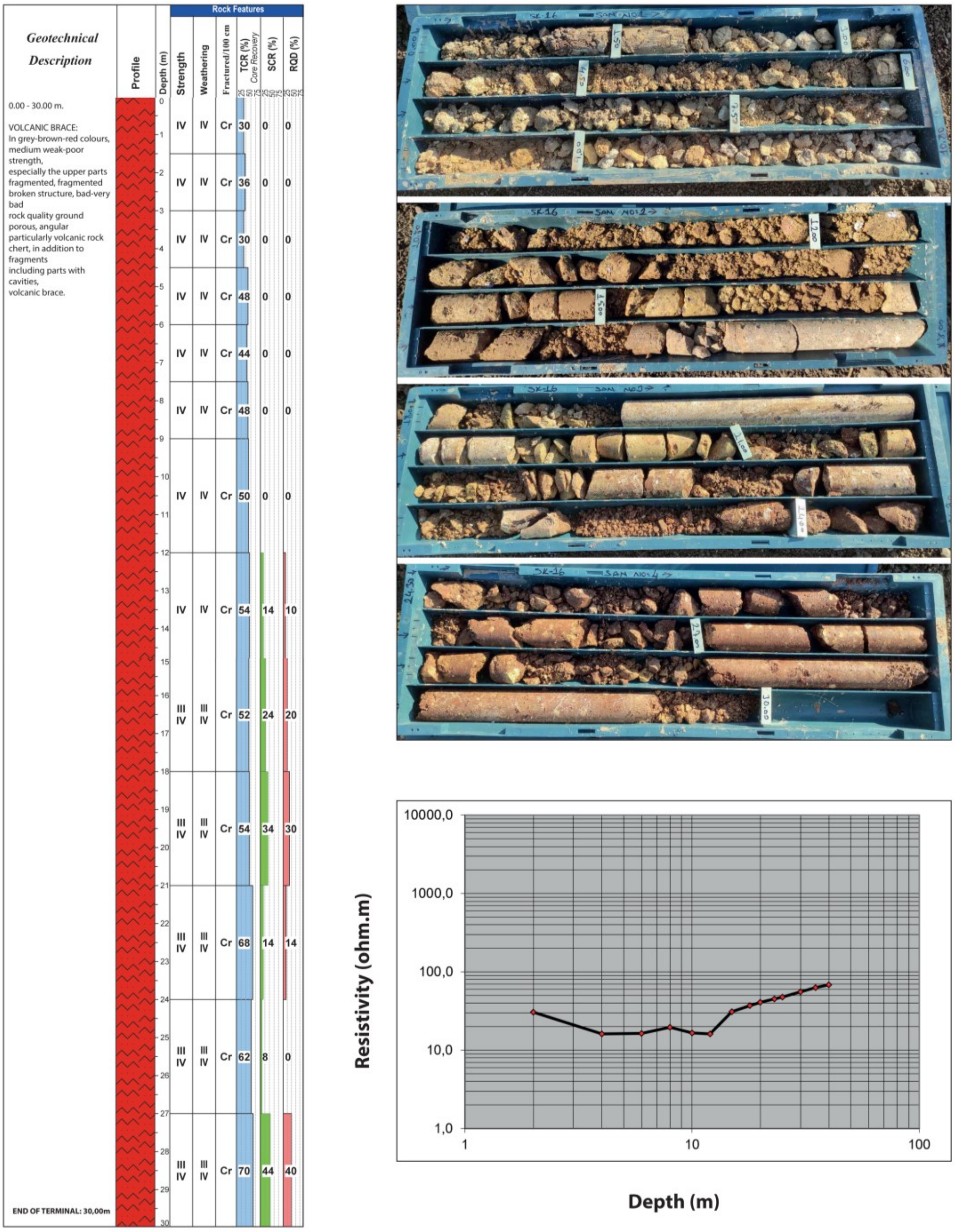


Weathering		Strength		1 m Fractures	RQD	
W1	Fresh	V	Very Weak	< 1 Wide (W)	%0-25	Very Poor
W2	Slightly W.	IV	Weak	1-2 Moderate (M)	%25-50	Poor
W3	Moderatly W.	III	Moderatly Weak	3-10 Close (Cl)	%50-75	Fair
W4	Highly W.	II	Moderatly Strong	10-20 Intense (I)	%75-90	Good
W5	Completely W.	I	Strong	>20 Crushed (Cr)	%90-100	Excellent

Figure 11. Comparison of DES-8 measurement curve (borehole SK-8 location) and diamond core drilling results (borehole log and the views of core boxes).

The RQD of borehole SK-16 is close to 0% (Figure 12). According to the borehole log and core box photography, basalt/volcanic breccia is completely altered. Resistivity values of 16.2-68.8 ohm.m were measured at DES-16 (borehole SK-16 location) (Figure 12). These values are pretty low for basalt-type rocks. Therefore, based on geologic observations, it can be evaluated that the DES-16 measurement location contains highly altered basalts/volcanic breccia.

The study observed a positive correlation between resistivity and RQD values (rock quality). In other words, the higher the rock quality (tendency towards strength rock), the higher the resistivity values. As the rock quality decreases (tendency towards weak rock), the resistivity values also decrease. These results are consistent with those obtained by Gemail et al. (2020), Hasan et al. (2023), Junaid et al. (2024), and Kahraman & Öğretici (2024).



Weathering		Strength		1 m Fractures	RQD	
W1	Fresh	V	Very Weak	< 1 Wide (W)	%0-25	Very Poor
W2	Slightly W.	IV	Weak	1-2 Moderate (M)	%25-50	Poor
W3	Moderatly W.	III	Moderatly Weak	3-10 Close (Cl)	%50-75	Fair
W4	Highly W.	II	Moderatly Strong	10-20 Intense (I)	%75-90	Good
W5	Completely W.	I	Strong	>20 Crushed (Cr)	%90-100	Excellent

Figure 12. Comparison of DES-16 measurement curve (borehole SK-16 location) and diamond core drilling results (borehole log and the views of core boxes).

2D geoelectrical model

To better interpret the curves and evaluation results obtained from VES measurements in the study area and the geoelectrical structure, the geological structure prepared 2 cross-sections in NW-SE and SW-NE directions in RockWorks software (Figure 13).

Cross-section A-A' is in the NW-SE direction (Figure 13). It was prepared by correlating the data of DES-4, DES-1, and DES-2 measurements. Resistivity values are slightly higher at point DES-4. From point DES-4 to point DES-2, resistivity values decrease considerably, causing rock quality to decrease. This result is consistent with the borehole cores.

Cross-section B-B' is in the SW-NE direction (Figure 13). It was prepared by correlating the data of DES-16, DES-1, and DES-8 measurements. Resistivity values are slightly higher at the point DES-1. At DES-16 and DES-8, resistivity values decrease considerably, causing rock quality to decrease. This result is also consistent with the borehole cores.

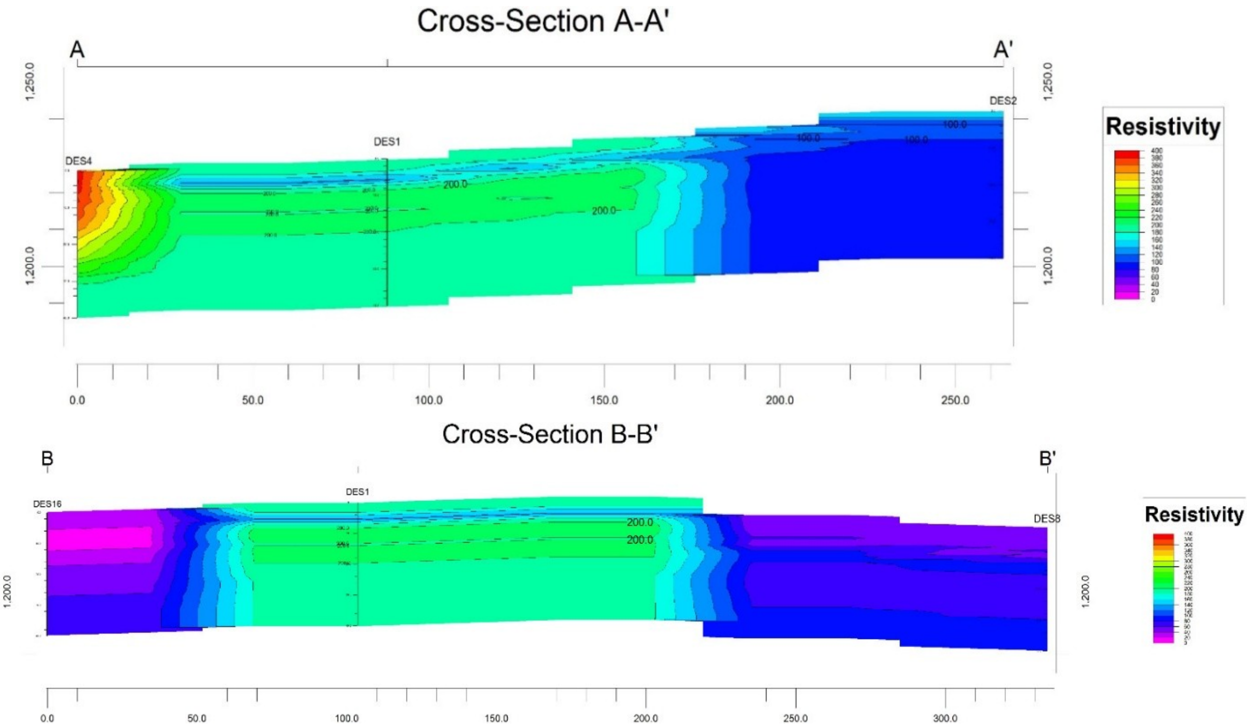
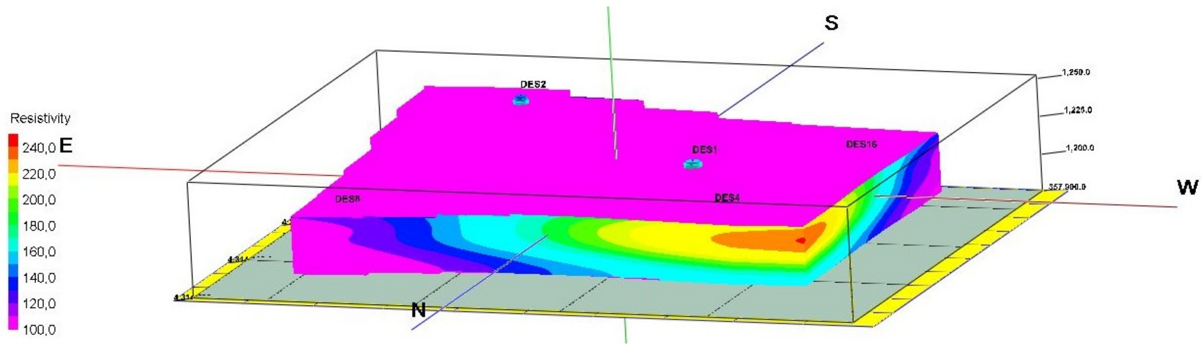


Figure 13. Geoelectrical cross-sections along profiles A-A' and B-B' (see Figure 7).

3D geoelectrical model

Nowadays, it has become possible to transfer the raw resistivity values measured from the field to the computer environment and to perform 3D modelling. The raw resistivity values and coordinates measured from the field are entered into the software as data. A 3D model is obtained using 'Grid Model' (network modelling) and geostatistical methods. The 3D resistivity model prepared for the study area is given in Figure 14, and the fence diagrams are shown in Figure 15. 3D resistivity models (solid model and panel diagram) are presented with different directional views to interpret the thickness and distribution of the massive basalt in the study area.

The resistivity values measured for the basalts in the study area are pretty low (16.1 - 390.9 ohm.m). This indicates that the basalts measured up to 40 m depth in the study area are mainly altered. The region where the study area is located is geothermally rich. Therefore, it seems to be the most probable reason that the basalts in the study area have been altered by geothermal/hydrothermal fluids rising from the surrounding faults. Although the study area is generally unsuitable for the supply of basalt, it is predicted that some crushed stone can be obtained from DES-4 and DES-1, which have relatively high resistivity values, and for ballast material from the surrounding parts of these VES measurements.



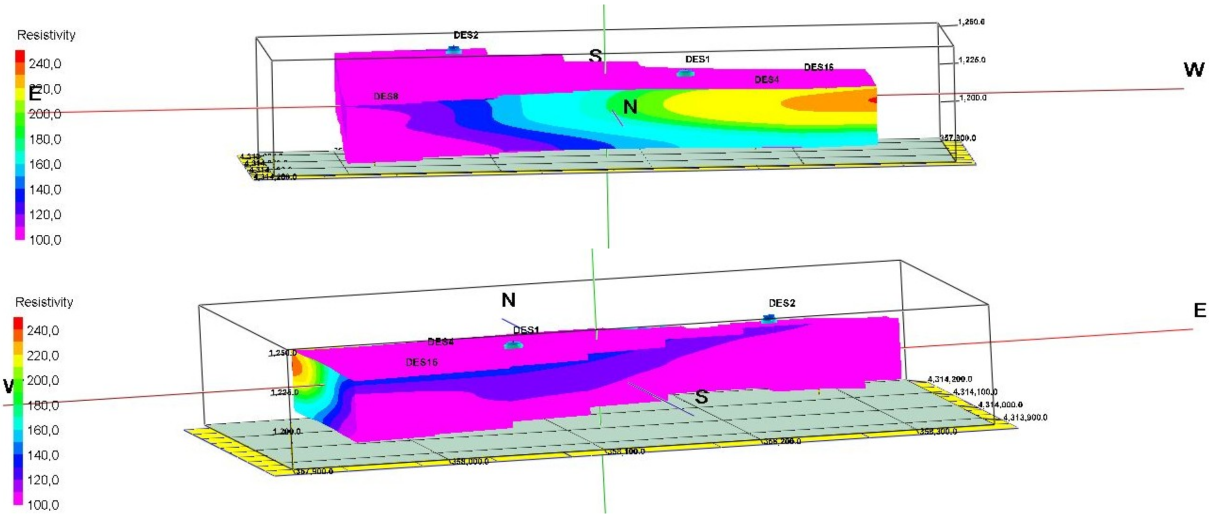


Figure 14. 3D model of resistivity measurements in the study area.

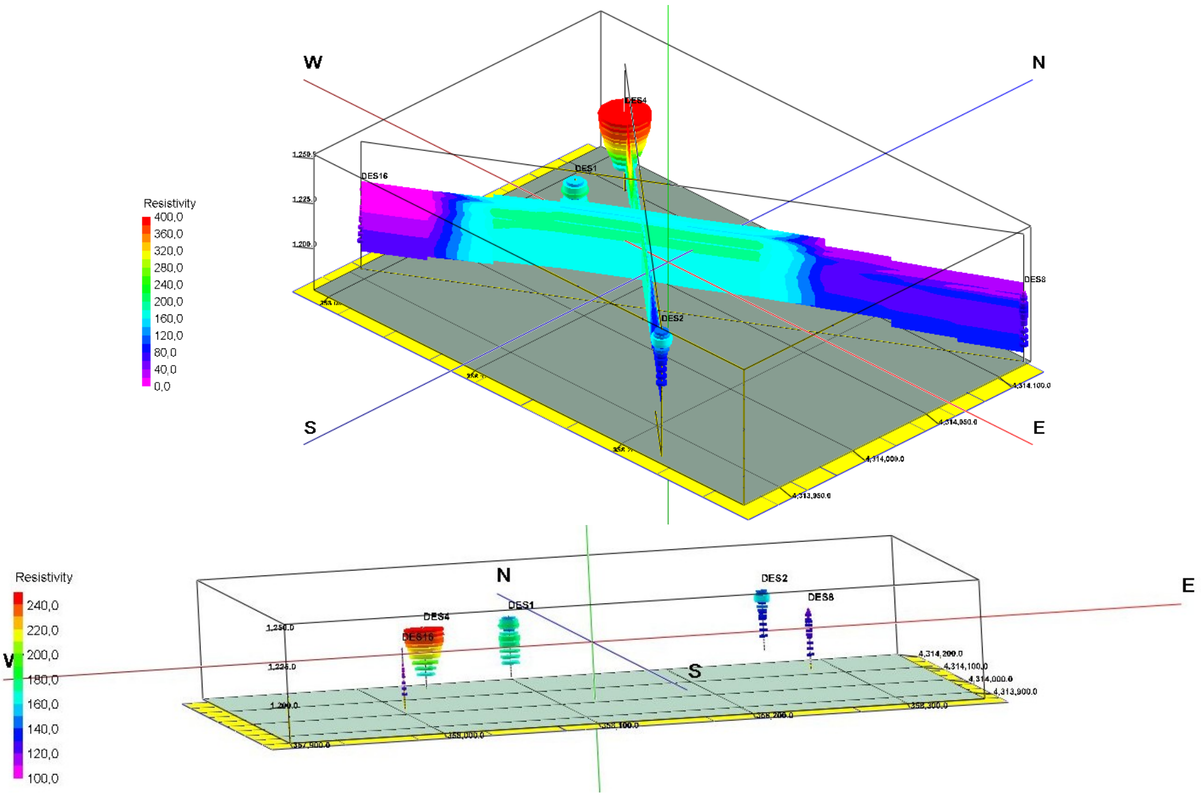


Figure 15. Fence diagrams of resistivity measurements in the study area.

Conclusion

According to the results of diamond core drilling in the study area, the site was not considered suitable for quarrying due to basalts' very low core recovery. For this reason, geophysical measurements were made with the VES to compare the relationship between core recovery and resistivity values of the boreholes drilled in the study area. Resistivity measurements showed very low resistivity values, which may belong to altered basalts instead of strength basalt-type rocks. These results obtained from resistivity measurements were also checked with gravity and magnetic maps. The results of drilling and geophysical surveys were found to be entirely compatible. Thus, while the suitability of the diamond core drilling results in the study area was confirmed, it was concluded that the first-stage suitability of a potential site for quarrying could be reliably evaluated with resistivity measurements, gravity, and magnetic data before drilling studies. This first stage of suitability assessment by geophysical methods can reduce the number of drillings to be carried out on the site. It will also contribute to reducing the cost of quarry site research.

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