

## Application of 2D inversion of apparent resistivity and RQD data in identification of granite massif quality

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### Summary

Collecting geotechnical information of subsurface formations is very important in creating water transfer structures and digging tunnels. Knowing the quality of rock structures in this regard can be done with the help of using geoelectric techniques. In order to determine the different subsurface geological structures and the quality of the granite rocks, the apparent resistivity data were collected by Vertical Electric Sounding (VES) method with the Schlumberger array in Glass area, located in the northwest of Iran. By performing two-dimensional inversion of the data using the Res2DInv software, tomograms of resistivity values distributed along each profile are constructed. Then, the obtained geoelectric sections are interpreted by means of geological and boreholes information to delineate the different rock structures in the study area. The study area includes all the weathering grades of formations from sandy soil to fresh rock. The results of the tests conducted on the samples taken from the boreholes drilled in the study area serve as a direct check for the results of the resistivity measurements interpretation. Interpretation results can provide an evaluation of the advantages and limitations of the geophysical method used. They also can depict a structural model of subsurface rock masses, showing the relationship between physical properties and geotechnical parameters like Rock Quality Designation (RQD) and the degree of weathering. In the geoelectric sections, resistivity variations in both vertical and horizontal directions are linked to different geological structures and discontinuities. The quality of granite rock masses, in terms of compaction or weathering, is assessed by analyzing resistivity values within the geoelectric sections. These findings on the quality of granite rock masses are compared and validated against borehole sample test results.

**Keywords:** Geotechnical information, granite, inversion, resistivity, rock quality designation (RQD)

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## 1 Introduction

Granite is an igneous rock, which means it formed from magma, or melted rock. It originates deep within the Earth when this molten material cools and crystallizes. Over time, wind, ice, and water erode the overlying mountains or volcanoes, gradually exposing the granite at the surface. The high temperature of magma impacts its surroundings, creating a phenomenon called contact metamorphism. The extent of this metamorphism varies depending on the temperature and distance from the heat source. The granite massif, under tension from the surrounding environment, experiences various forces. Through the years, as the surrounding layers erode, the pressure on the massif decreases, causing it to expand. This expansion leads to the formation of joints and fractures. Additionally, the varying depth of magma and distance from the Earth's surface cause differences in the orientation of feldspar crystals within the granite, which can manifest as layers (Sawyer, 1998). Resistivity measurements are an important and integral component of geoelectrical investigations connected with environmental problems. In recent years, electrical resistivity surveys have progressed rapidly from the conventional sounding survey, which provides layer depths and resistivities at a single location, to techniques which provide two-dimensional electrical images of the subsurface. The geoelectrical technique is among the most widely used geophysical methods in a broad range of environmental studies (Maill et al., 2005; Soupios et al., 2006). The purpose of electrical surveys is to determine the subsurface resistivity distribution by making measurements on

the ground surface. From these measurements, the true resistivity of the subsurface can be estimated using interpretation of measured apparent resistivity data through modeling and inversion techniques. The imaging technique from inverse modeling of measured apparent resistivity data is particularly powerful and useful in the study areas with complex geology, in groundwater problems and in many other shallow subsurface investigations (Dahlin, 1996).

The apparent resistivity data collected by different methods can be interpreted by different inversion methods such as two-dimensional electrical imaging technique. The results of this technique can help delineate various subsurface rock structures, including granite, especially when there is a significant variation in subsurface resistivities (Sundaranar, 2012; Chiba et al., 1994). Electrical Resistivity Tomography (ERT) has recently become the most frequently used geoelectrical application for geomorphological purposes due to its relative simplicity and time effectivity. This technique has been applied to the investigation of morphotectonics (Suzuki et al., 2000), weathering studies (Beauvais et al., 2006), fluvial geomorphology (Maill et al., 2005), permafrost detection (Hauck and Kneisel, 2006), and exploration of underground karst structures (Zhou et al., 1999). ERT is particularly suitable for identifying the depth and internal structure of various types of slope deformations (Batayneh and Al-Diabat, 2002; Lapenna et al., 2003; Bichler et al., 2004; Lebourg et al., 2005; Drahor et al., 2006; Perrone et al., 2006; Sass, 2006; Sass et al., 2008; Van Den Eeckhaut et al., 2007).

In the absence of complex terrain

restrictions, an attempt was made to characterize a granite massif in north-west Spain along two different profiles to determine its geotechnical qualities and variability. This was achieved by integrating results from seismic refraction, multichannel analysis of surface waves and electrical resistivity tomography methods (Olona et al., 2010).

The two-dimensional electrical imaging method was performed by measuring apparent resistivity data using the Schlumberger array along several profiles in order to reveal subsurface boulders. Images from inverted resistivity data successfully identify the existence of boulders in the area of investigation in the topsoil region, characterized by high resistivity values. Whereas, only one core log out of three reported the presence of boulders (Junaid et al., 2019).

Junaid et al. (2022a, b, c) conducted an ERT survey for subsurface geological delineation of granite deposits. The results obtained from the geophysical survey and boreholes information were further processed to estimate the bedrock to topsoil ratio to assess the feasibility of the deposit. The study demonstrated that ERT is an inexpensive, viable, and efficient technique for the subsurface delineation of granite deposits.

Rock Quality Designation (RQD) is a standard technique in mining and geotechnical investigation for quantifying the quality and degree of jointing of rock mass based on the RQD index. Although drill core is the primary way of estimating RQD and it provides reliable information at specific points, large numbers of cores are needed for accurate and detailed subsurface geological descriptions, which is excessively costly and time-consuming.

Additionally, as many rock-cut slopes are located in complex morphological areas, drilling survey is not always possible in many cases. Therefore, the indirect estimation of RQD from discontinuity frequency, termed as scan-line survey, is suggested to circumvent the limitation of core drilling. However, the calculation of RQD from the scan-line survey is directional dependent, that is, the value of RQD may vary in different directions at the same site (Tsang et al., 2022; Kring and Chatterjee, 2020; Sonmez et al., 2022). To reduce the limitation of the scan-line survey, a correlation between Volumetric Joint Counts (Jv) and RQD is suggested (Buen and Palmstrom, 1982). The Jv refers to the number of joints present in a unit volume of the rock mass.

Another indirect method of estimating RQD values that is used for geotechnical and engineering applications is the unmanned aerial vehicle (UAV) method which provides an accurate, denser, richer, and more exact 3D point cloud (Junaid et al., 2022c). Nevertheless, estimating Jv from the UAV 3D point cloud is time-consuming, particularly for large areas. In addition, the calculation of RQD on a 3D point cloud is impossible in a highly vegetated area (Ismail et al., 2022). Furthermore, the UAV point cloud provides surface assessment only, while subsurface rock mass quality remains unexposed.

To solve the problems stated above, 2D Electrical Resistivity Tomography (2D ERT) provides a promising approach by offering a low-cost, reliable, advanced data collection and interpretation, and a non-destructive technique for subsurface rock mass quality characterization (Junaid et al., 2021, 2022a, 2022b, 2023). The ERT

method has also been widely used for rock engineering applications, such as slope rock stability assessment (Falae et al., 2019), dam health assessment (Zumr et al., 2020) and landslide detection (Carrion-Mero et al., 2021).

Although the RQD method can be used to determine the quality of rock masses, due to the limitations of direct access to this data, efforts are made to access the quality of subsurface rock masses based on the RQD index by using the 2D ERT method (Ishak et al., 2020; Lin et al., 2021).

The combined methods of 2D ERT method, UAV and borehole sampling were used to assign the values of resistivity to different indices of RQD values. In fact, the purpose of UAV survey was to reconstruct a 3D point cloud and calculate the RQD values on a rock outcrop or surface indirectly using  $J_v$ , whereas the 2D ERT survey provided the corresponding resistivity values. In other words, the purpose of the 2D ERT survey was to extract the corresponding resistivity values for various RQD indexes. On the other hand, the sole aim of the borehole survey was to validate the RQD and corresponding resistivity values obtained from the UAV and the 2D ERT survey. The k-Nearest Neighbour (k-NN) analysis was also performed to assign resistivity values to various RQD indexes. The primary aim of k-NN was to categorize the data into various classes. The k-NN classification was performed for two types of correlation such as RQD and resistivity, and  $J_v$  and resistivity (Junaid et al., 2024).

In resistivity measurement technique, the resistivity data were generated using different electrode arrays which can be resulted in pseudo-sections with sampling of apparent resistivity

measurements at different depths. The measured resistivity data later being edited, processed, and inverted using 2D inversion approach, gives 2D true resistivity models. The maximum depth of investigation is shown in the resistivity models along the vertical axis and is determined by the spacing between the electrodes and the number of electrodes used in the specific type of array. However, it also depends on geology and heterogeneity of the subsurface formation.

A traditional exploration technique, especially for evaluating granite resources, is drilling, but even a limited number of drilling samples are unsuccessful in accurately drawing the boulders. Because the drilling is limited to small points and the rock is heterogeneous, its features cannot be accurately identified through the drilling method. Thus, to image the subsurface boulder layer in a granite deposit, a combination of electrical resistivity and borehole techniques can be used.

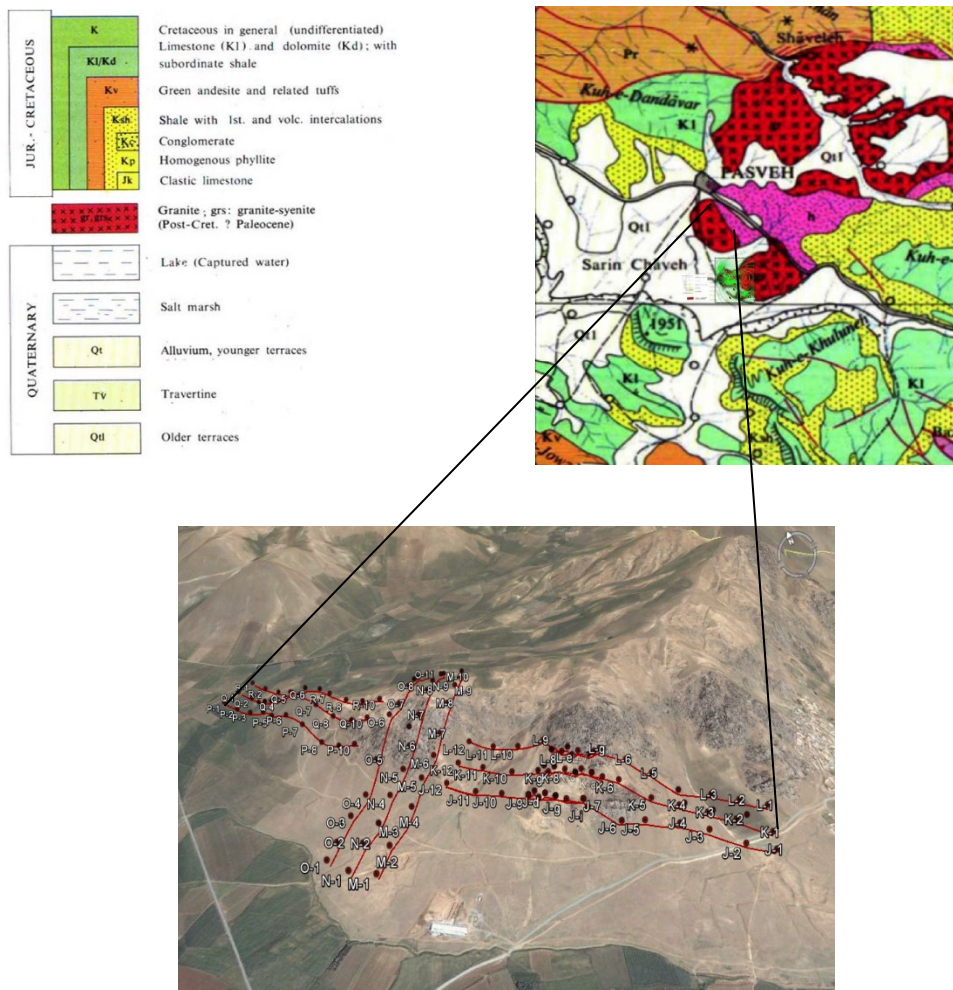
In present study, measured vertical apparent resistivities data by Schlumberger array are used to identify the granite intrusion and quality of the rocks in the Glas area in NW of Iran. Then, these data are interpreted to map the hardness and compaction of the granitic bodies from the resistivity values of the overburden material in the study area. The delineation of higher resistivity contrast and the low resistivity values of the weathered overburden are used to locate a suitable site for mining of granite at study area. The information such as logs data, RQD data and thin sections was used to achieve this investigation. In the end, by correlating the values of distributed electrical resistivities in the drawn 2D geoelectric sections with other available

information, a detailed description of the granitic mass, metamorphic contacts, faults and the relationship between the RQD data and the aforementioned distributed electrical resistivity values is provided.

## 2 Geological setting

The Glas area is located in the Kurdistan district, in the southern part of West Azerbaijan province. Geographically, it marks the northwest boundary of the Zagros Mountains and is defined by longitudes 45°30' and 46" and latitudes 36°30' and 37". This region covers an

area of 2500 km<sup>2</sup>, with 90% of the land consisting of solid outcrops. The topography is characterized by mountainous terrain, with an average elevation of around 1800 meters. The area features several parallel ranges with sharp peaks. The central mountains form a gently arched range trending north-south, aligning with the general direction of the mountain system. The central part of this zone includes several parallel, gently arched ranges, surrounded by sharply crested ranges composed of Cretaceous, Paleozoic, Infra-Cambrian, and carbonate rocks (see Fig. 1).



**Figure 1.** Geology map with three dimensional view of the area combined with the topography and location of the electrical soundings.

Fig. 1 shows the area map, the locations of electrical soundings, and the profile information. According to the geological map, the formation consists of granite, metamorphic rocks, and alluvial deposits. The area is situated between farmland and alluvial regions. The electrical soundings are spaced approximately 50 meters apart, which provides greater accuracy compared to larger distances. Three boreholes were drilled through the granite and alluvial formations. A Rock Quality Index (RQI) has been proposed to assess rock mass quality, with changes in the RQI versus depth depicted in subsequent diagrams. Log data from the region categorize rock quality into five classes: very poor, poor, fair, good, and very good.

### 3 Methodology

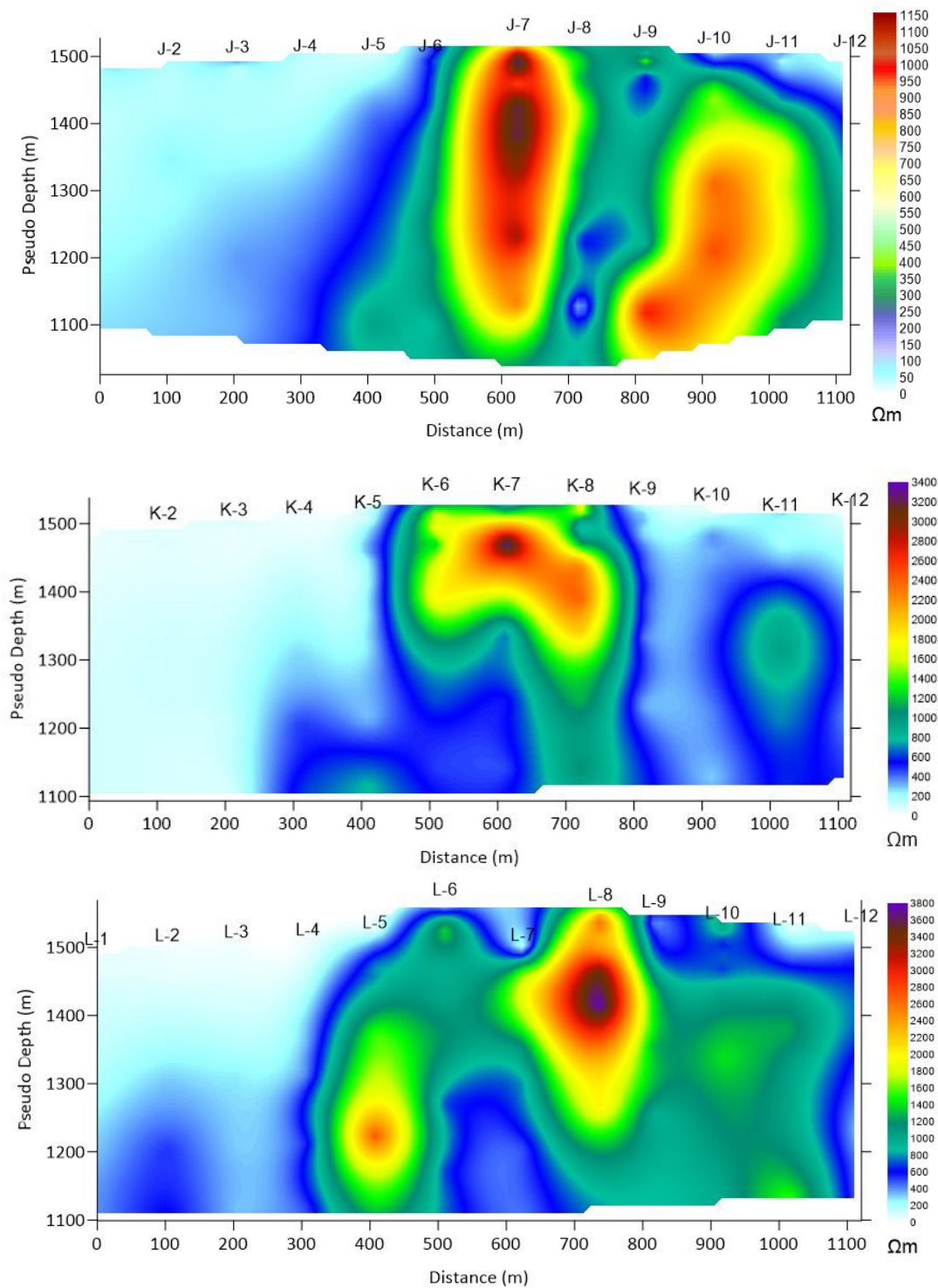
After conducting field studies in Glass area of northwest of Iran, 124 electrical soundings using the Schlumberger method were performed along several profiles (Fig. 1). The distance between the soundings was 50 meters. Apparent resistivity data, plotted against half the current electrode spacing, were interpreted by fitting them to two-layer standard curves. The results from these matching curves were then optimized using 1-D inversion of the apparent resistivity data. The 1-D inversion results provided the thickness and resistivity of the layers beneath each sounding location. Subsequently, for each profile, a pseudo-section of distributed apparent resistivity values was created to qualitatively describe the subsurface material properties. From these pseudo-sections, rock structures, as well as granite and fault zones, were

identified based on the range of resistivity values. Additionally, 2-D resistivity sections were constructed using Res2DInv software (Loke, 2004), based on the inversion of all apparent resistivity data along the profiles. Interpretation of the resistivity contours on these sections provided more detailed geological images of the subsurface formations. These images offer valuable insights into the rock formations, particularly regarding the quality of the granitic mass in this area.

### 4 Two dimensional apparent resistivity pseudo-sections

A cross-section of apparent resistivity illustrates the variations in resistivity across subsurface structures. To visualize these variations which reflect general changes in the quality of subsurface structures, pseudo-sections for all profiles were created using Surfer software (Figs. 2 and 3).

The quasi-three-dimensional distribution of the apparent resistivities measured along different profiles is displayed in Fig. 4. In this figure, the region with higher values of distributed apparent resistivity can be clearly seen, which can be related to rock formations that have higher quality and hardness. In aforementioned figures, regions with high apparent resistivity, located at the center of the profile, likely indicate the presence of igneous rocks such as granite formations. The surrounding areas with lower resistivity values may represent sedimentary deposits or different rock formations. Sudden changes in apparent resistivity near the igneous rock can be interpreted as fractures, faults, or variations in material.



**Figure 2.** Two dimensional pseudo-sections of apparent resistivity of profiles J, K and L.

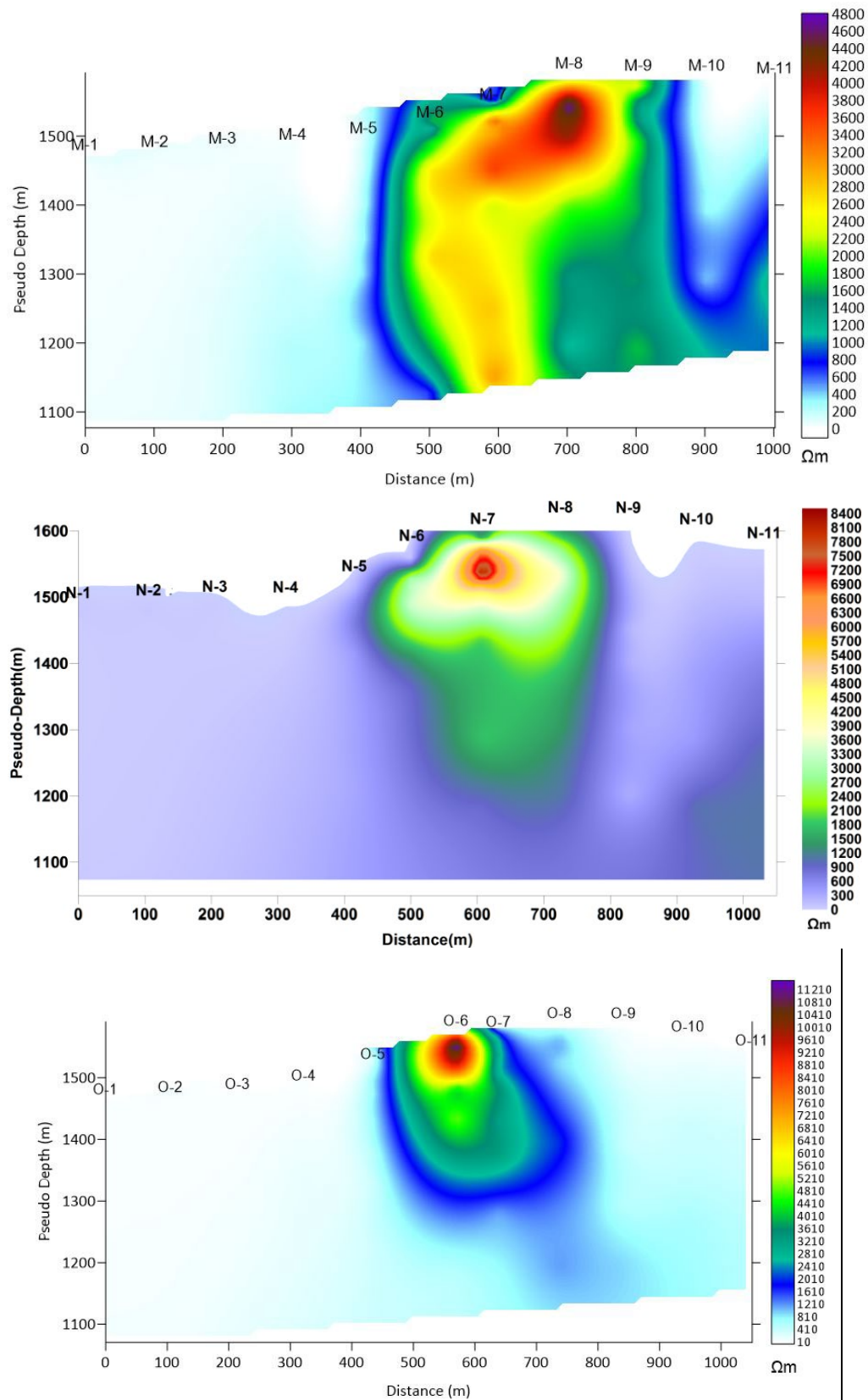
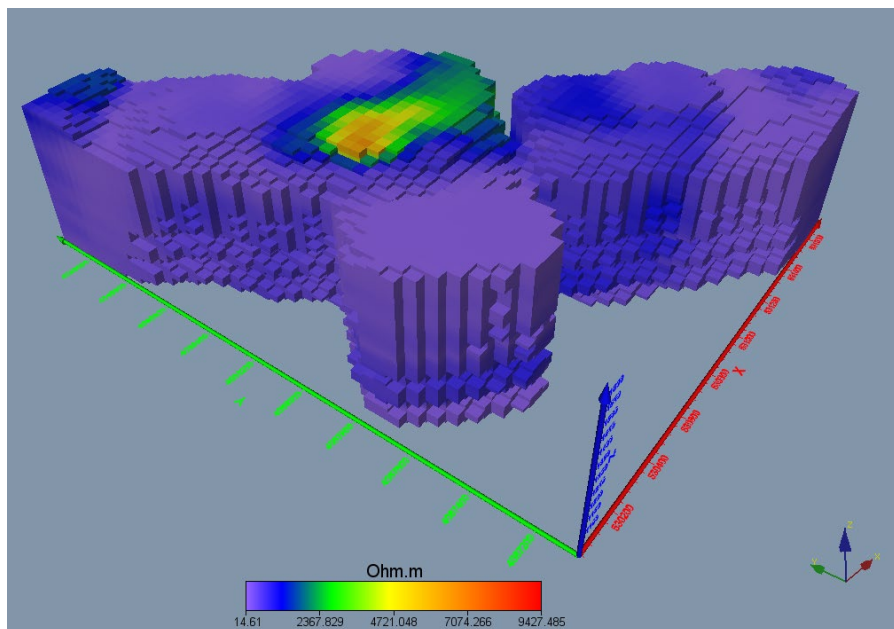


Figure 3. Two dimensional pseudo-sections of apparent resistivity of profiles M, N and O.

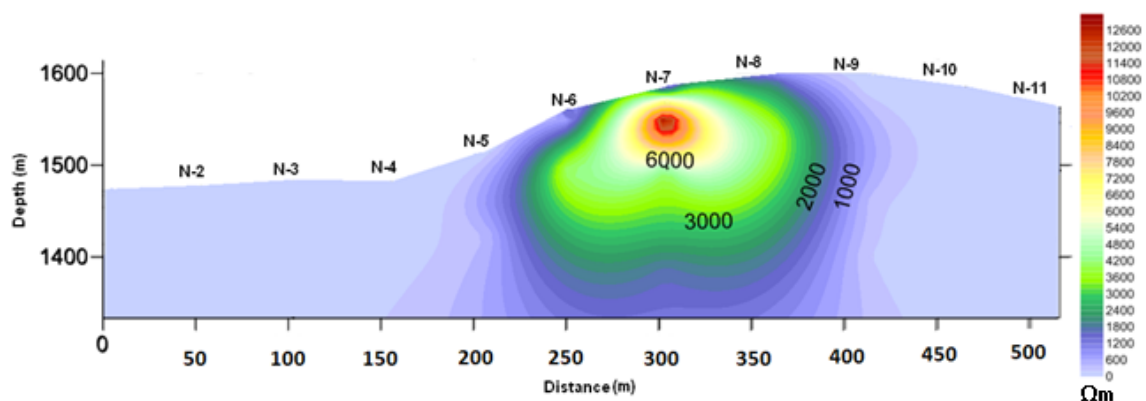


**Figure 4.** A three-dimensional view of the distribution of apparent resistivity values taken along different profiles.

### 5 The pseudo-sections of resistivities

These pseudo-sections can be formed by the results of the interpretation of the apparent resistivity data outcome with fitting apparent resistivity data of each sounding by standard two layers curves and then, optimizing the results, resistivity and thickness of the layers below each sounding position by doing

1-D inversion and with the use of geological information in the area. These pseudo-sections can present more realistic aspects of subsurface geological features. The sections were constructed and plotted for all profiles. Here, only one of the most prominent of these sections is shown in Fig. 5.



**Figure 5.** Two-dimensional pseudo-sections of resistivity along profile N.

At this pseudo-section, a zone with high resistivity value separated and located near the surface is recognizable. Resistivity with low and moderate values

around the zone is related to the formation of alluvial and probably weathered granite rock which has rather low thickness. In this pseudo-section,

different parts with different resistivity values can be interpreted as geological formations such as: fine-grained alluvial (Qt1), medium grained alluvial deposits (Qt2), coarse-grained alluvial deposits (Qt3), weathered granite (Grw), granite (Gr) and hornfels (Hf). Sudden changes in the lateral resistivity can be attributed to the fractures or materials changes.

### 6 Two dimensional resistivity sections

Using the Res2DInv software, the inversion process steps had been conducted on the apparent resistivity data along each profile. The results of the inversion obtained from the six profiles, shown as cross sections, can be seen in Fig. 6 and next to each other in Fig. 7 as fence diagram.

The distribution of the resistivity observed on the section with different

colors can be interpreted as the presence of different geological formations. In this section, high resistivity values are related to the existence of granitic intrusion mass. Area with higher resistivity values can be considered as granite rocks which have higher quality. Moreover, zones with high resistivity values, interpreted as granite rocks extended from depth to the surface, are distinguishable on the sections. As can be seen, resistivity values around these zones gradually decrease, and thus infer that the quality of the granite rocks degrade, which can be due to the presence of the weathering and fractures in the formation and the rocks. Reducing resistivity values at the surrounding mentioned granite zones, with increasing their distance from the zones, can be considered as metamorphism phenomena.

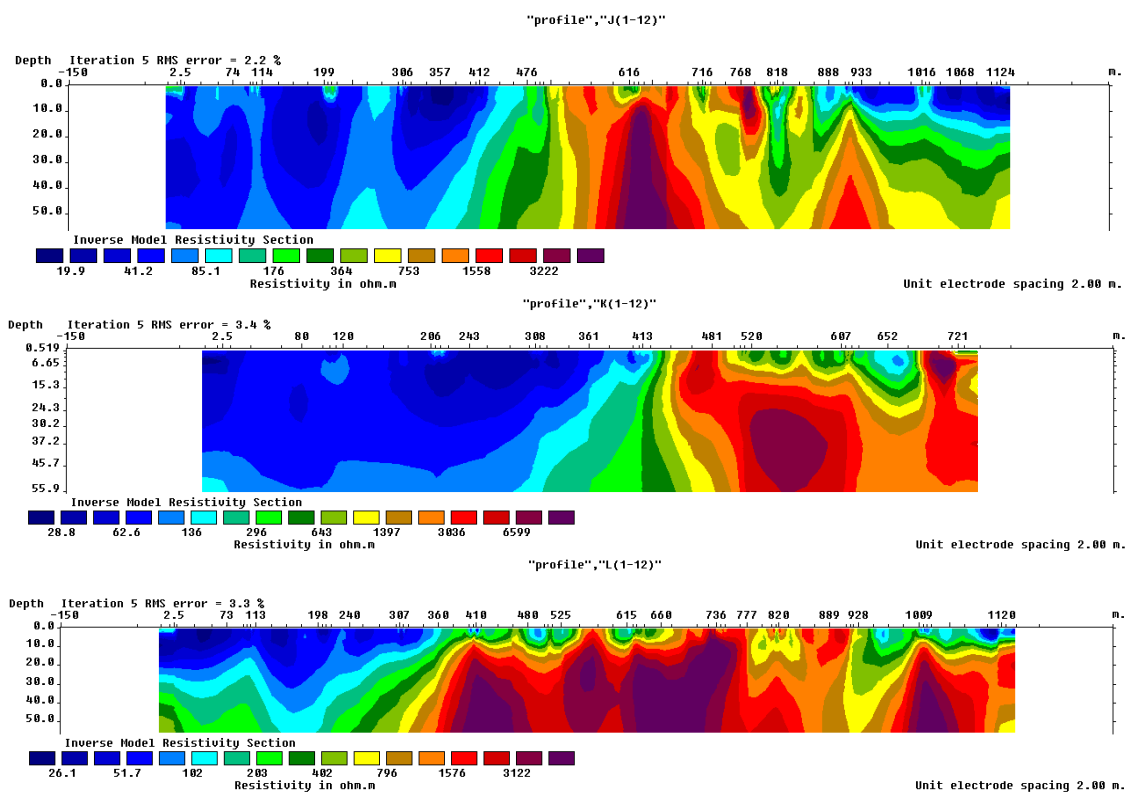
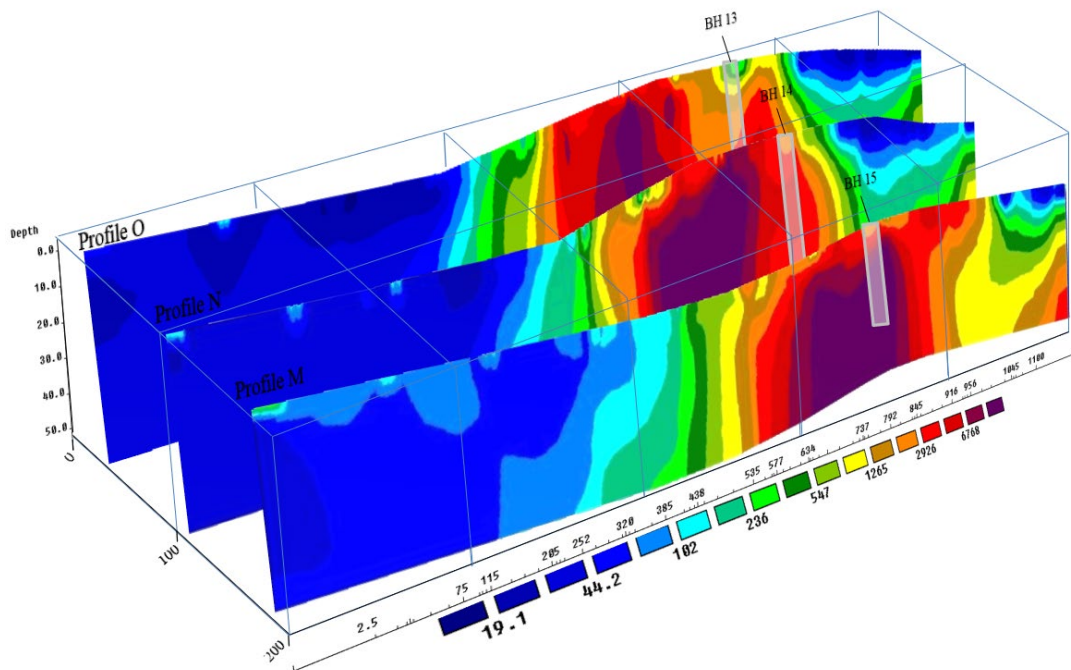


Figure 6. Two dimensional sections of resistivity of profiles J, K and L.



**Figure 7.** Two dimensional sections of resistivity of profiles O, N and M. The position of boreholes is also shown on the sections.

From Fig. 7, by considering the distance between the profiles, the span and mass of granite rocks for proposed mining and civil engineering applications can roughly be estimated. In addition, sudden changes in resistivity values, especially around the granite rock, can be considered as an indication of the fault zone or other tectonic activities.

We know that in order to be able to establish a meaningful relationship between the values of resistivities distributed on the geoelectric sections and the quality of the rock, it is necessary to have information about the quality of the rock obtained from the boreholes located either on the sections or near them. Since in this research, only the information related to the boreholes located on the sections M, N and O is accessible, the focus has been on the analysis of obtaining this relationship for the mentioned sections.

RQD is a measure of quality of rock

core taken from a borehole. It signifies the degree of jointing or fracture in a rock mass and is measured in percentage. RQD of 75% or more shows good quality hard rock and less than 50% shows low quality weathered rocks. It is used to evaluate quality of rocks such as degree and depth of weathering, zones of rock weakness and fracturing. This information is used for determining the depth of foundations, bearing capacity of rocks, settlement and sliding possibilities of foundations. RQD helps in obtaining favorable tunneling conditions and evaluating the zones with poor quality rocks which may not support the engineering structures. In the study area, RQD information has been accessible through drilling boreholes, which have been used to better interpret the inversion results of resistivity measurements.

The connection between three boreholes RQD logs and resistivity sections of profiles O, N and M can be

seen in Fig. 8. As it is obvious, the information of RQD sections shows a relatively good match with electrical resistivity section results at the locations of the boreholes. This shows a very good relation between RQD and electrical resistivity of rocks. The figure shows that the quality of rock formations increases from the surface to the depth, which can be clearly seen in both the RQD and the resistivity sections.

The images indicate presence of the low resistivity zone and low RQD values at the top of the surface of profile and one high zone and high RQD data at the other sides. There is a high correlation between high resistivity values and high RQD data in the sections.

The correlation shown between the geoelectric and the RQD sections indicates that it is possible to obtain appropriate information about the quality of subsurface rock formations without expensive and time-consuming excavations. Of course, if there are suitable conditions, creating a borehole (or boreholes) in the study area and collecting appropriate information from it (them) can effectively help to better interpret the apparent resistivity data measurement on the surface of the earth.

**Table 1.** Rock quality in terms of RQD percentage values.

Rock Quality	RQD value (%)
Very poor	0-25
Poor	25-50
Fair	50-70
Good	70-90
Very good	90-100

Good matching of RQD data between three logs can be seen in Fig. 8. Rock quality in terms of RQD percentage values is shown in Table 1. In the figure, the levels with different colors from cold to warm show the rock quality index from very poor to very good ones. Good

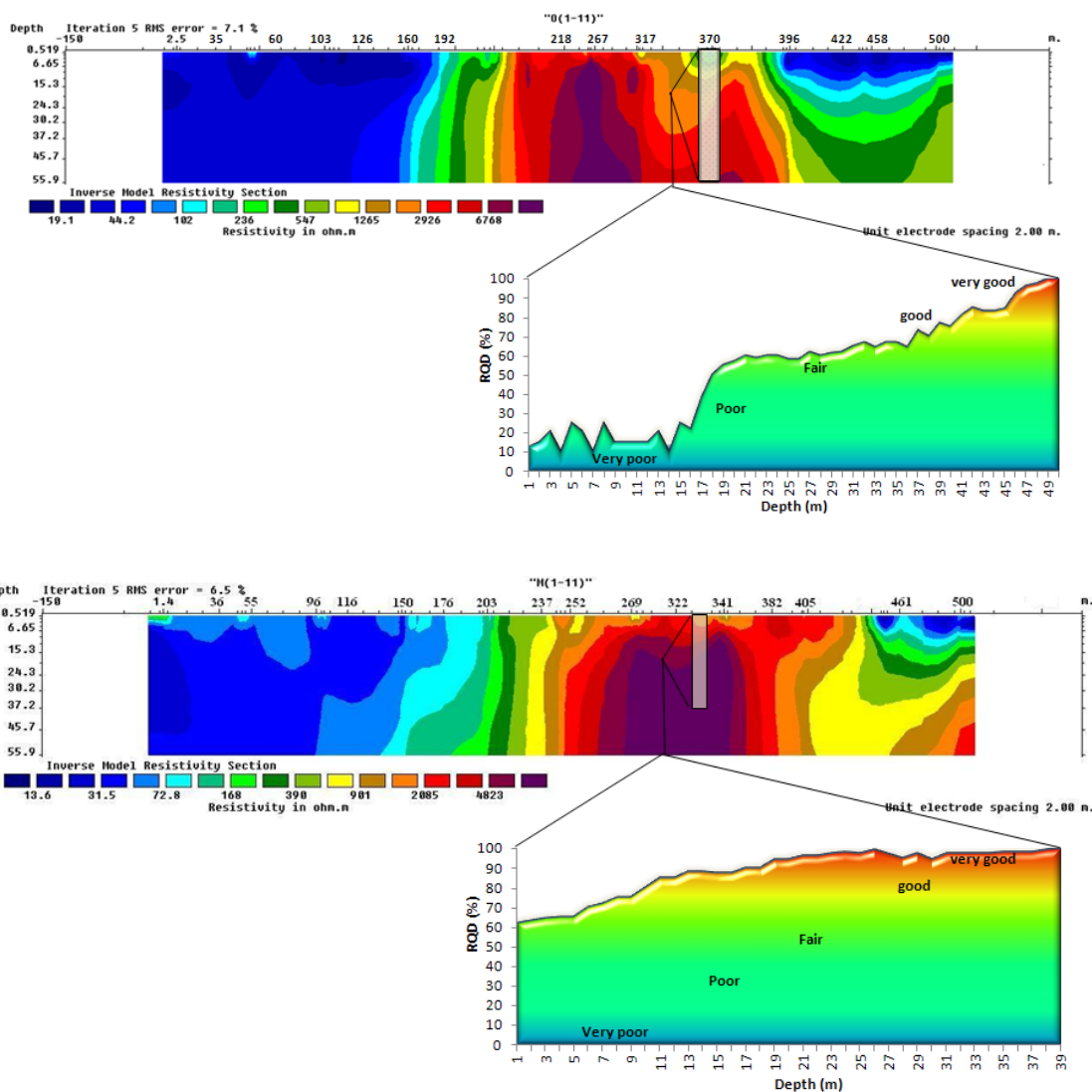
correlation between resistivity and RQD data is also presented in the Fig. 9. The left illustration shows the RQD and the right one is the resistivity of soundings and boreholes at the position of profiles O, N and M. The higher and lower RQD ratio and resistivity are represented by warm and cold colors. Hence such changes in the resistivity values can be shown as different dimensions of feldspar and remained tension. It is obvious that the colors of both illustrations have a clear similarity with high correlation. Using the thin sections of borehole at the location of O showed there are different orientations of feldspars in different depths (Fig. 10). The comparison between RQD and electric results reveals there are some relations between these features presented clearly in the figures (thin sections, RQD and electric illustrations). These images represent there are layers in granitic mass. Moreover, they show the electric resistivity and RQD relate directly to the feldspar directions in granite and it may be the cause of the diffraction phenomena at the forming intrusion mass times.

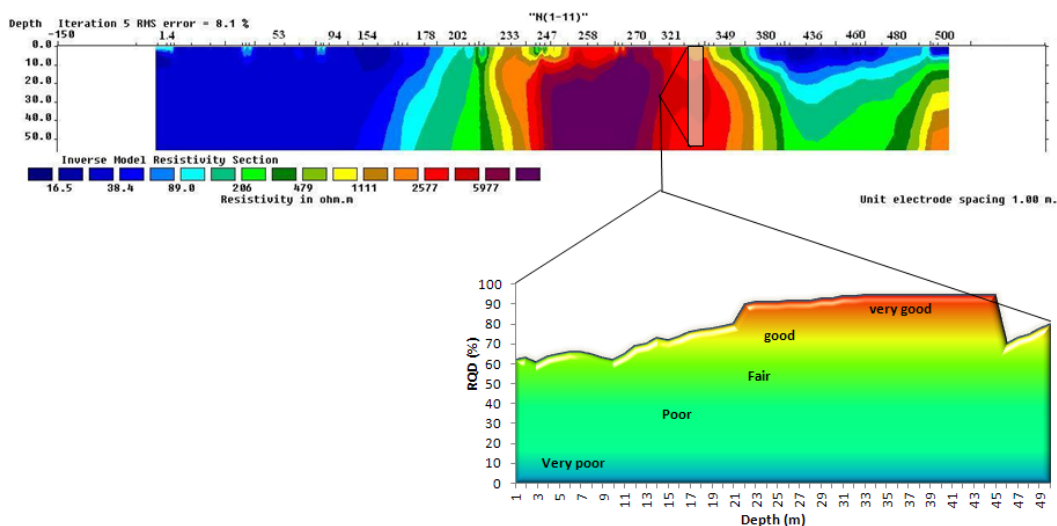
## 7 Conclusion

To obtain a comprehensive understanding of subsurface structures, especially rock formations, and to describe them both qualitatively and quantitatively, it is beneficial to supplement borehole data with measurements of apparent resistivities on the Earth's surface. This geophysical method provides valuable information efficiently, saving both time and money. In this study, the interpretation of measured geoelectrical data revealed zones of granite intrusive igneous and metamorphic rocks. Geological logs

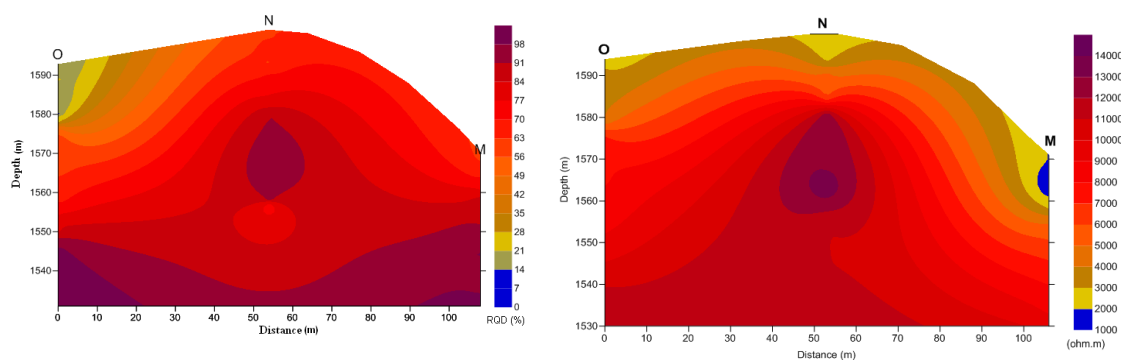
served as supplementary data. By analyzing apparent resistivity along various profiles and correlating these with regional geology, it was demonstrated that high resistivity values are associated with granitic masses, while lower values may indicate weathered granite or alluvial sedimentary formations. This interpretation also allowed for the identification of weathering, fractures, and compactness in the granitic rocks,

which is crucial for mining and civil engineering activities. Furthermore, the study provided valuable information regarding the distribution and quality of granite, which can be used as a foundational reference for mining and civil engineering projects. Correlations between geological features from RQD, resistivity, and thin section measurements showed good consistency at several sites.

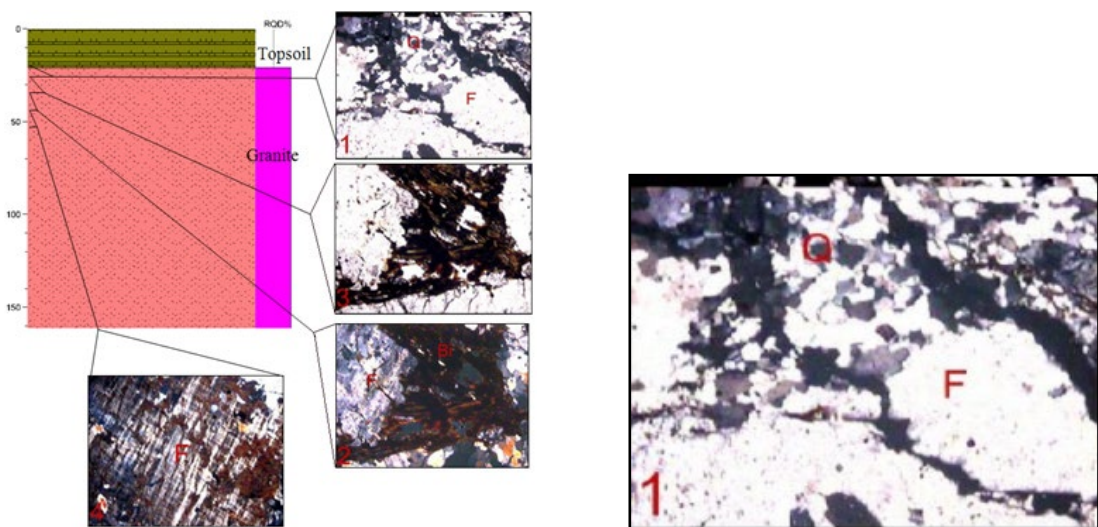




**Figure 8.** The resistivity models obtained from the inversion process for the O, N, and M profiles along with the positions of the corresponding logs. Additionally, mass qualities versus depth are displayed below each model.



**Figure 9.** Comparison between RQD (right side) and resistivity (left side) of the O, N, M profiles in the location of boreholes and soundings, respectively.



**Figure 10.** The log and thin sections at different depths related to the borehole positioned on the resistivity section of the O profile. On the thin sections, the letters F, Bi and Q indicate the presence of chemical elements Feldspar, Bismuth and Quartz. The numbers 1, 2 and 3 refer to the section numbers.

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