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Application of the Electrical Resistivity Method in Precision Agriculture of Coffee Cultivation, in the Kabiri Area, Ícolo e Bengo Township, Luanda, Angola

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Abstract

The electrical resistivity method is a geophysical tool used to characterize the subsoil and can provide an important information for precision agriculture. The lack of knowledge about agronomic properties of the soil tends to affect the agricultural coffee production system. Therefore, research related to geoelectrical properties of soil such as resistivity for characterization the region of the study for coffee cultivation purposes can improve and optimize the production. This resistivity method allows to investigate the subsurface through different techniques: 1D vertical electrical sounding and electrical imaging. The acquisition of data using these techniques permitted the creation of 2D resistivity cross section from the study area. The geoelectrical data was acquired by using a resistivity meter equipment and was processed in different softwares. The results of the geoelectrical characterization from 1D resistivity model and 2D resistivity electrical sections show that in the study area of Kabiri, there are 8 varieties of geoelectrical layers with different resistivity or conductivity. Near survey in the study area, the lowest resistivity is around 0.322 Ω·m, while the highest is about 92.1 Ω·m. These values illustrated where is possible to plant coffee for suggestion of specific fertilization plan for some area to improve the cultivation.

Keywords

Electrical-Resistivity Method, Precision Agriculture, Coffee

1. Introduction

Precision agriculture involves steps such as data acquisition, data analysis, planning and implementation of decisions made [1]. It is a technology that mainly consists in increasing production efficiency and profits based on the differentiated management of an area in agriculture and making different decisions for the same area regarding its preparation and fertilization [2]-[5].

In Angola, coffee is cultivated in several provinces with different ecological characteristics, producing different types of coffee trees with particular attributes. In the study area, there is agricultural potential for coffee cultivation, however, the lack of knowledge of the characteristics of its soils, compromises the agricultural coffee production. Therefore, the implementation of new sustainable agricultural production techniques, such as the application of geophysical electrical resistivity methods in precision agriculture, can be a key to start the coffee production and satisfy the population's demand for coffee and other foods in that county.

Currently, the Electrical Profiling and the Vertical Electrical Sounding (VES) surveys of the electrical resistivity method have been used by geophysicists in agricultural studies [6]. The mapping of conductivity and resistivity of a certain area, allows the identification of water conductive and resistive zones, compact zones, salinity zones, soil types and structures, and thus determines the proper management of agricultural soils and its agricultural production capacity [6]-[9].

The appropriate soil conditions for coffee cultivation taking into account the electrical resistivity, vary between 10 and 100 Ω·m, meanwhile, for the electrical conductivity it is between 0.1 and 1.0 S/m. In the case of the Arabica coffee, which is the most cultivated variety in the world, the ideal conditions for resistivity vary from 20 to 50 Ω·m, while, for electrical conductivity it is from 0.2 to 0.5 S/m [10].

The aims of this research are 1) create a geoelectrical model of the study zone with its resistive layers through a theoretical resistivity raw data obtained in the field; 2) characterize the area of study in terms of resistivity and conductivity for the purposes of coffee cultivation and 3) propose other types of agriculture and soil treatment processes, taking into account the interpreted resistivity values and lithologies.

Study Area

Kabiri, the study area, is located in Kabiri town of Ícolo e Bengo township, in Luanda province, Angola, approximately bounded by the geographic coordinates of 08˚54'55"S and 13˚40'09"E. The study area has an area of approximately 4.5 km2, and it is approximately 324 m away from the Quilunda lake (**Figure 1**). The climate is hot and dry while the local vegetation includes Savanna with bushes, trees, herbal Savanna and Balcedos. Furthermore, there is a predominance of chromic Luvissol soils type, which generally occur with high nutritional potential rich in potassium and high silt contents with a surface crust varying from 5 to 10 mm thick.

2. Geologic Setting

The degree of geologic setting of the area is insufficient. Nonetheless, studies made

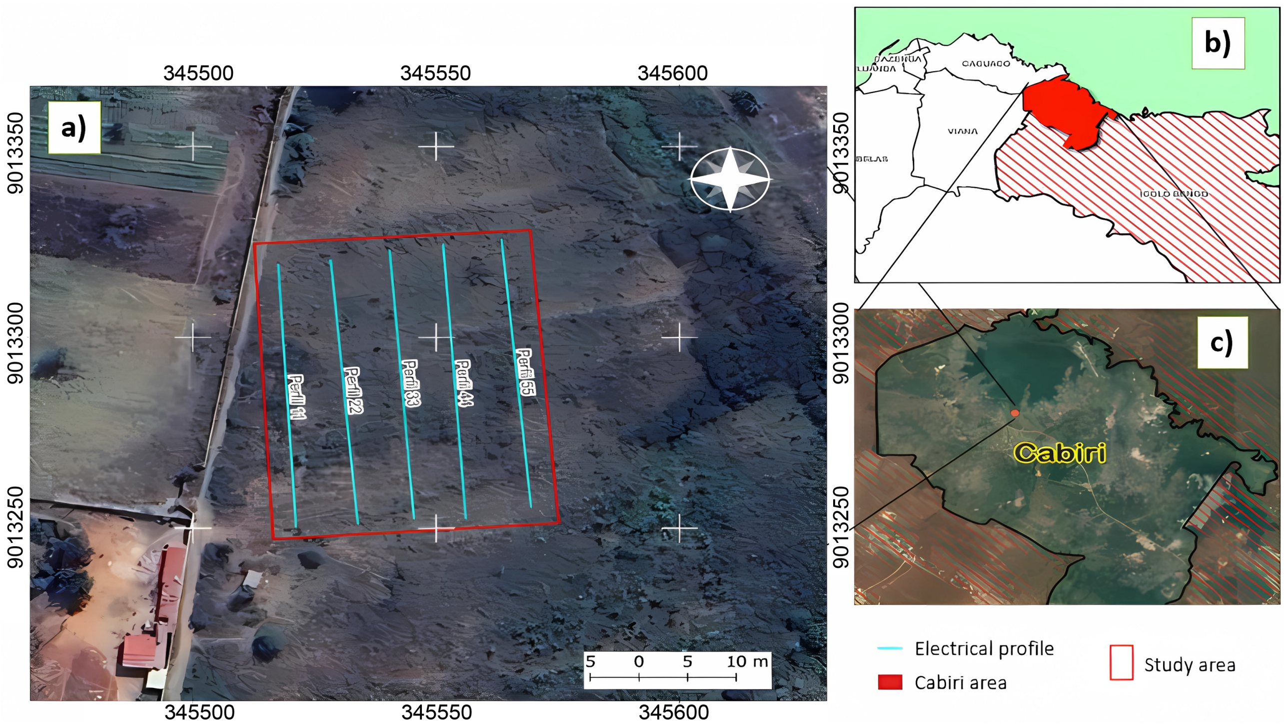

Figure 1. The location map of the study area. (a) Is the map of data acquisition grid with 5 electrical profiles; (b) and (c), illustrate the study area in Kabiri.

by [11] [12], show that in the study area there are two geologic formations. The Quifangondo formation and the Bom Jesus formation which make part of the Lunda Formations deposited in the Oligocene-Miocene period (**Figure 2**). The Quifangondo formation is compound by sandy-clay rocks, limestone sediments, gypsum sediments, intercalations of marls, dolomites and conglomerates whose thickness can reach 3013 meters. Conversely, the Bom Jesus formation is made up of marls, clays and rarely lime-stone and sandstone with thickness is around 120 meters.

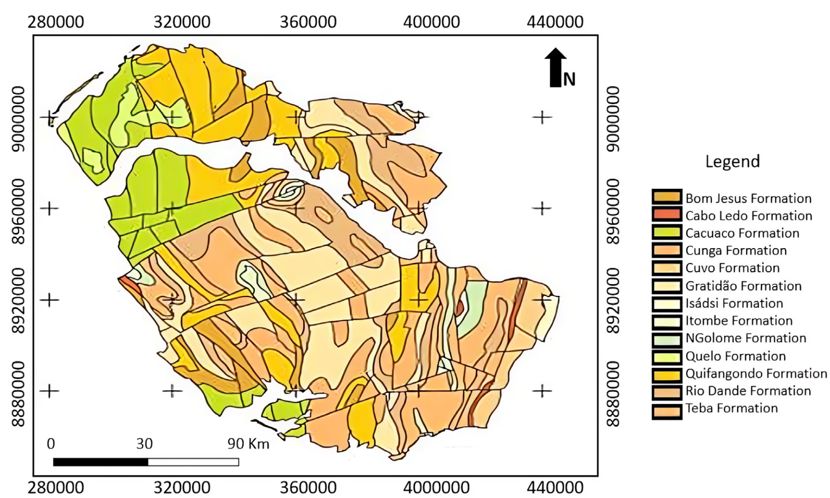

Figure 2. Geological formations of Luanda with the studied geo-logical formations [12].

3. Materials and Methods

The resistivity and conductivity survey data for soil study started with the recognition of the study area to define the profile lines. A grid data survey was designed in an area of 20.000 m^2 where five 2D geoelectrical sections were defined (profile: PROFL-11, PROFL-22, PROFL-33, PROFL-44, PROFL-55) with 70 m length each and separated by 10 m. 2D geoelectrical sections were conducted using 15 electrodes arranged on the straight line following the Wenner-Schlumberger array, which consisted of measuring 40 points up to 5 subsurface investigation levels for a single line (Figure 3(h)). For minimize the interpretation of resistivity and conductivity data in the 2D geoelectrical sections, a vertical electrical sounding survey (VES) was acquired between the profile lines PROFL-11 and PROFL-22 (Figure 3(a), Figure 3(h), Figure 3(i)). In this survey was used the Schlumberger array configuration with up to 20 electrodes and was measured 10 data points of resistivity according to electrodes spacing AB up to 50 m as shown in schematic image of the survey in Figure 3(i) and Table 1.

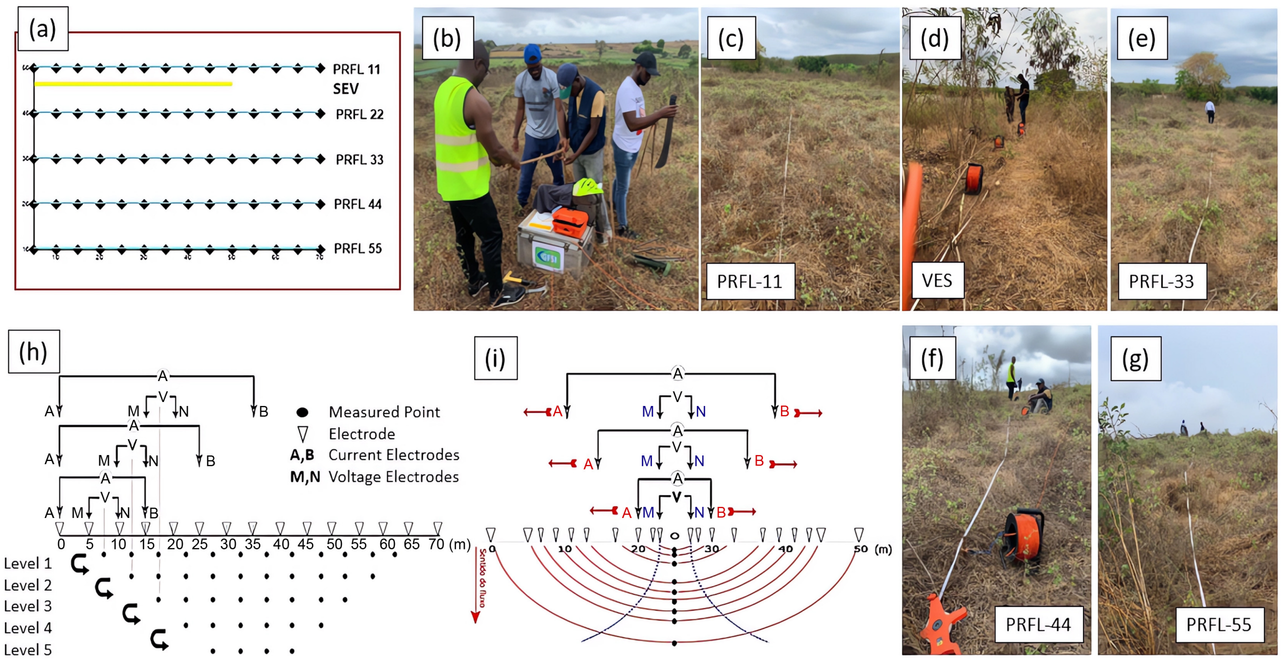

Figure 3. Data acquisition design. (a) grid data survey; (b) Resistivity Meter equipment; (d) the Vertical Electrical Sounding (VES) line; (c), (e), (f) and (g) are profiles 11, 22, 33, 44, and 55; (h) the electrical profiling survey (a total depth of investigation of 15 m for each profile) with a Wenner-Schlumberger geometry containing 15 electrodes and 5 levels of investigations, (i) vertical electrical sounding (VES) survey with a symmetric array configuration Schlumberger with 20 electrodes.

During the acquisition data for the VES, the midpoint of the array containing the measuring electrodes (*MN*) remained constant, while the current electrodes (*AB*) were being increased to obtain a 1D distribution of resistivity of rocks with depth. For the data of electrical profiles were obtained by moving the fixed acquisition geometry with the current electrodes (*AB*) and the measuring electrodes (*MN*) to laterally study the resistivity of the area [7] [13] [14]. The measured electrical apparent resistivity for the Schlumberger and Wenner configurations, was defined using the Equation (1);

$$\rho a = K\frac{\Delta V}{I} \tag{1}$$

where $K = 2\pi\left(\frac{1}{AM}-\frac{1}{BM}-\frac{1}{AN}+\frac{1}{BN}\right)^{-1}$ is the geometric factor, ΔV is the potential difference (voltage—V) and I is the current intensity (A).

The electrical conductivity, which is the inverse of the electrical resistivity from the five profiles, was calculated using the Equation (2):

$$\sigma = \frac{1}{\rho} \tag{2}$$

where: σ —Electrical conductivity (Siemens/m); ρ—resistivity (ohm meter).

For data acquisition was used a WDDS-2 Resistivity Meter equipment that includes 2 current electrodes (AB) and two measuring electrodes (MN), connected to D.C battery (**Figure 3(b)**). This equipment allowed to measure the resistivities in varies data points along profile lines and VES. The resistivity values measured by the equipment represent apparent resistivity values because these values are influenced by several factors such as the heterogeneity of the soil and the type of array used to acquire the data. To obtain the true values of the measured (or observed) resistivity, the data was processed with Earth Imager 1D and Res2Dinv software to remove noise and invert the data to have the true resistivity of the subsurface. The inversion used by Res2Dinv program is based on the smoothness-constrained least-squares method. One advantage of this method consists of by is that its factors and filters can be adjusted to different types of data [15] [16]. The smoothness-constrained least-squares method is explained by the following equation:

$$\left(J^{T}J+\beta F\right)q = J^{T}g-\beta Fq \tag{3}$$

where: J is Jacobian matrix of partial derivation, J^T is the transpose of J, β is the damping factor, F is an identify matrix that describes the layer structure, q is the model change vector and g is the data misfit vector.

Table 1 shows the acquisition data from SEV that was used to create theoretical curve of apparent resistivity data. The processing of these data consisted of inversion using the Damped Square Least Inversion method followed by an adjustment of the theoretical curve values (**Figure 4**). This inversion reduced the negative effects of soils compaction and topography on the resistivity and generated of the final 2D geoelectrical model of the study area. Similar processing procedures were used for processing all five profile lines of resistivity and conductivity raw data through Res2Dinv software. These procedures included: uploading and organization of resistivity and conductivity raw data from **Table 2** into the Res2Dinv software; configuration of inversion parameters such as the initial damping factor, minimum damping factor and high damping values; the generation of the electrical resistivity sections and their inverse models and finally the application of the inversion.

Table 1. Example of data obtained from a SEV using the Schlumberger configuration, showing the values of apparent resistivity that was measured in 10 points.

INDEX	AB/2 (m)	MN/2 (m)	RESISTIVITY (Ω·m)
1	2	1	5106
2	3	1	2847
3	5	1	4657
4	8	2	2879
5	12	2	3346
6	14	2	256
7	16	2	20,943
8	18	2	37,076
9	20	2	4125
10	25	2	3932

4. Results and Discussion

Qualitative and quantitative interpretations were conducted to the geoelectrical models acquired in 1D Vertical Electrical Sounding and 2D resistivity cross section were carried out to identify layers and their variations along study area. Data from SEV (**Figure 5(b)**) shows that in the study area there are approximately 8 geoelectrical layers indicated by red arrows in **Figure 5(a)** and cover up to 10 m depth. The resistivity of the layers was associated with geology around the study area and its values were compared with papers [7] [11] [17] are as follow: 20.1 Ω·m was interpreted as silty boulder; 2.27 Ω·m inferred as sandy silt; 1.32 Ω·m as claystone; 1.64 Ω·m considered as siltstone; 3.79 Ω·m as clay sand-stone; 5.88 Ω·m as silty limestone; 0.87 Ω·m as clay sand and 4.58 Ω·m inferred as marls.

Profile-11 survey in **Figure 6** illustrates that there are three regions with different characteristics in terms of resistivity (RES-1, RES-2 and RES-3). The resistivity intervals in this area are 0.624 - 3.30 Ω·m, 0.62 - 2.7 Ω·m and 92.1 - 130 Ω·m. These areas were geologically interpreted as siliceous limestone for high resistivity, clay sand for low resistivity and sandy silt for intermediate resistivity (**Figure 6(c)**), while the 2D geoelectrical section from profile-22 shows 2 resistive zones (RES-1; RES-2) or 2 conductive areas (COND-1; COND-2). The resistivity intervals in this area are 0.32 - 4 Ω·m and 269 - 826 Ω·m, indicating conductivity values that vary from 3.12 - 0.25 S/m and 0.003 - 0.001 S/m (**Figure 7**). According to [7] [17], these values from profile-22 can be geologically interpreted as marls for high resistivity, clay and sand for low resistivity and siltstones and mudstones for intermediate resistivity.

The profile-33 **Figure 8(a)** and **Figure 8(b)** show 2 conductive areas (COND-1; COND-2). The conductive in these areas varies from 0.19 - 2.39 S/m and 0.004 - 0.015 S/m. The two conductive areas were geologically interpreted as dolomitic limestone for high resistivity, clay sandstone and sandy silt for low and intermediate

Table 2. Data from the electrical profile (PRFL-11) - Wenner-Schlumberger configuration array. AB/2 and MN/2 are the acquisition parameters. SP-the electrical selfish potential; IP-the electrical current.

INDEX	AB/2 (m)	MN/2 (m)	RESISTIVITY (Ω·m)	SP (mv)	VP (mv)	IP (mA)
1	7.5	2.5	−2.139	−0.554	−1.149	16.871
2	7.5	2.5	−144.597	−49.253	−26.64	5.787
3	7.5	2.5	−20.128	−25.923	−12.84	20.042
4	7.5	2.5	3.264	−16.993	1.565	15.063
5	7.5	2.5	22.503	15.487	3.708	5.177
6	7.5	2.5	−1.27	−77.962	−0.393	9.715
7	7.5	2.5	1.928	−16.175	1.193	19.429
8	7.5	2.5	−0.507	36.667	−0.643	39.874
9	7.5	2.5	5.295	6.11	3.286	19.499
10	7.5	2.5	−0.649	25.544	−0.672	32.512
11	7.5	2.5	4.185	157.112	6.826	51.238
12	7.5	2.5	2.101	−72.03	2.171	32.462
13	12.5	2.5	2.626	−223.02	0.289	10.365
14	12.5	2.5	3.738	−64.524	1.27	32.021
15	12.5	2.5	19.649	2.367	8.585	41.177
16	12.5	2.5	30.804	84.001	3.863	11.82
17	12.5	2.5	2.845	−5.75	0.15	4.964
18	12.5	2.5	0.978	−127.01	0.14	13.449
19	12.5	2.5	2.711	98.718	0.621	21.591
20	12.5	2.5	2.489	87.49	0.998	37.802
21	12.5	2.5	−31.68	−0.951	−7.029	20.911
22	12.5	2.5	2.63	33.901	0.746	26.721
23	17.5	2.5	2.1	−85.58	0.235	21.124
24	17.5	2.5	2.586	51.012	0.361	26.327
25	17.5	2.5	3.062	93.35	0.563	34.64
26	17.5	2.5	2.522	−7.965	0.244	18.211
27	17.5	2.5	−599.475	−39.116	−16.01	5.034
28	17.5	2.5	2.601	83.472	0.166	12.06
29	17.5	2.5	2.07	87.876	0.266	24.185
30	17.5	2.5	23.642	−1.981	3.494	27.857
31	22.5	2.5	8.653	36.705	0.493	17.914
32	22.5	2.5	5.135	178.398	1.089	66.621
33	22.5	2.5	17.105	−6.225	2.296	42.17
34	22.5	2.5	−185.743	−53.351	−10.43	17.638
35	22.5	2.5	1.933	84.002	0.032	5.162

Continued

36	22.5	2.5	−356.005	−13.711	−10.6	9.356
37	27.5	2.5	−81.292	−5.484	−3.341	19.368
38	27.5	2.5	88.316	−1.7	12.129	64.716
39	27.5	2.5	6.564	−116.88	0.738	53.013
40	27.5	2.5	−131.779	4.784	−3.984	14.246

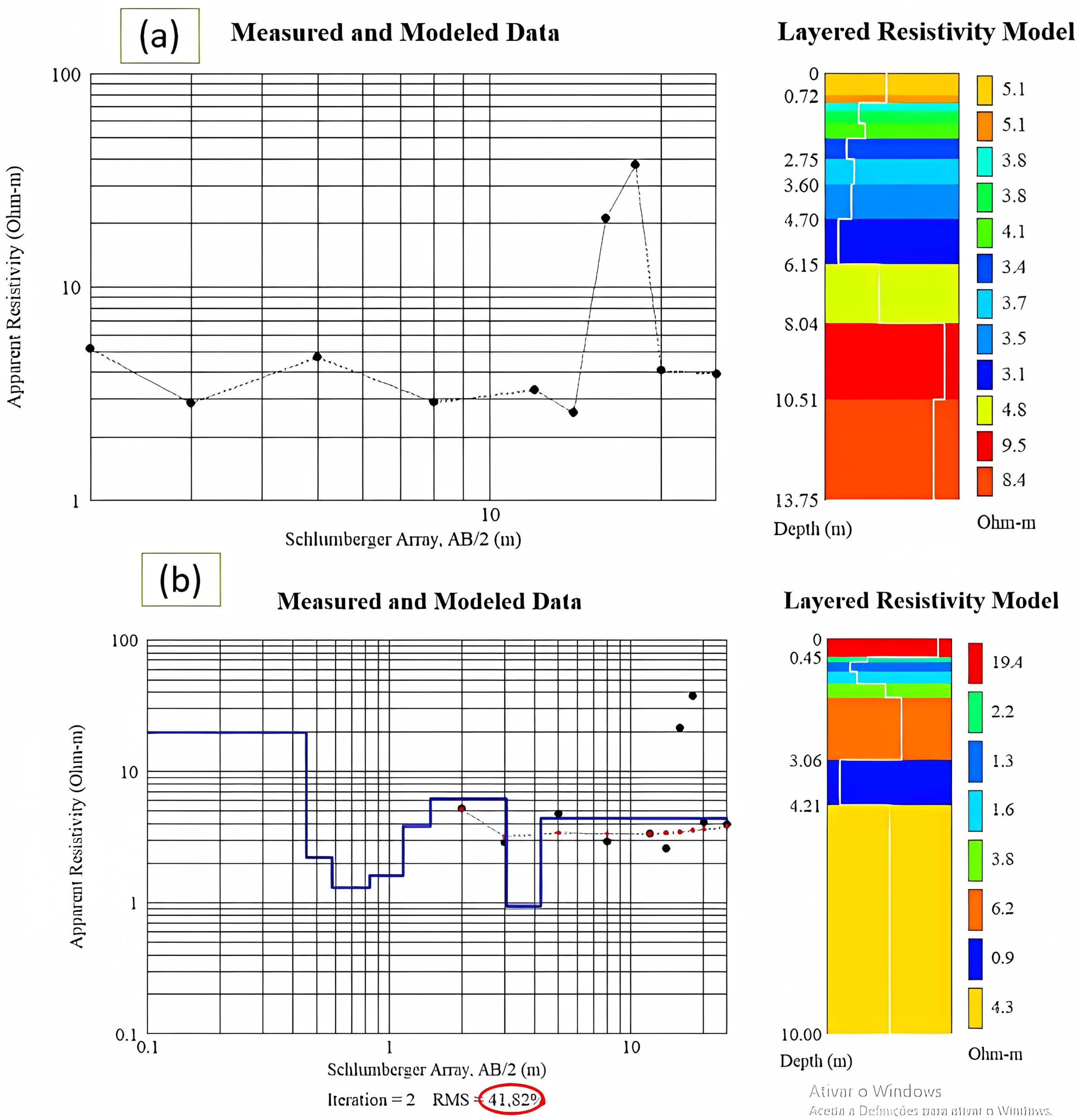

Figure 4. Data processing of the electrical line (SEV). (a) The generated geoelectrical model of resistivity data with its measured theoretical curve and depth; (b) The final geoelectrical model with number of iterations and a RMS of 41%.

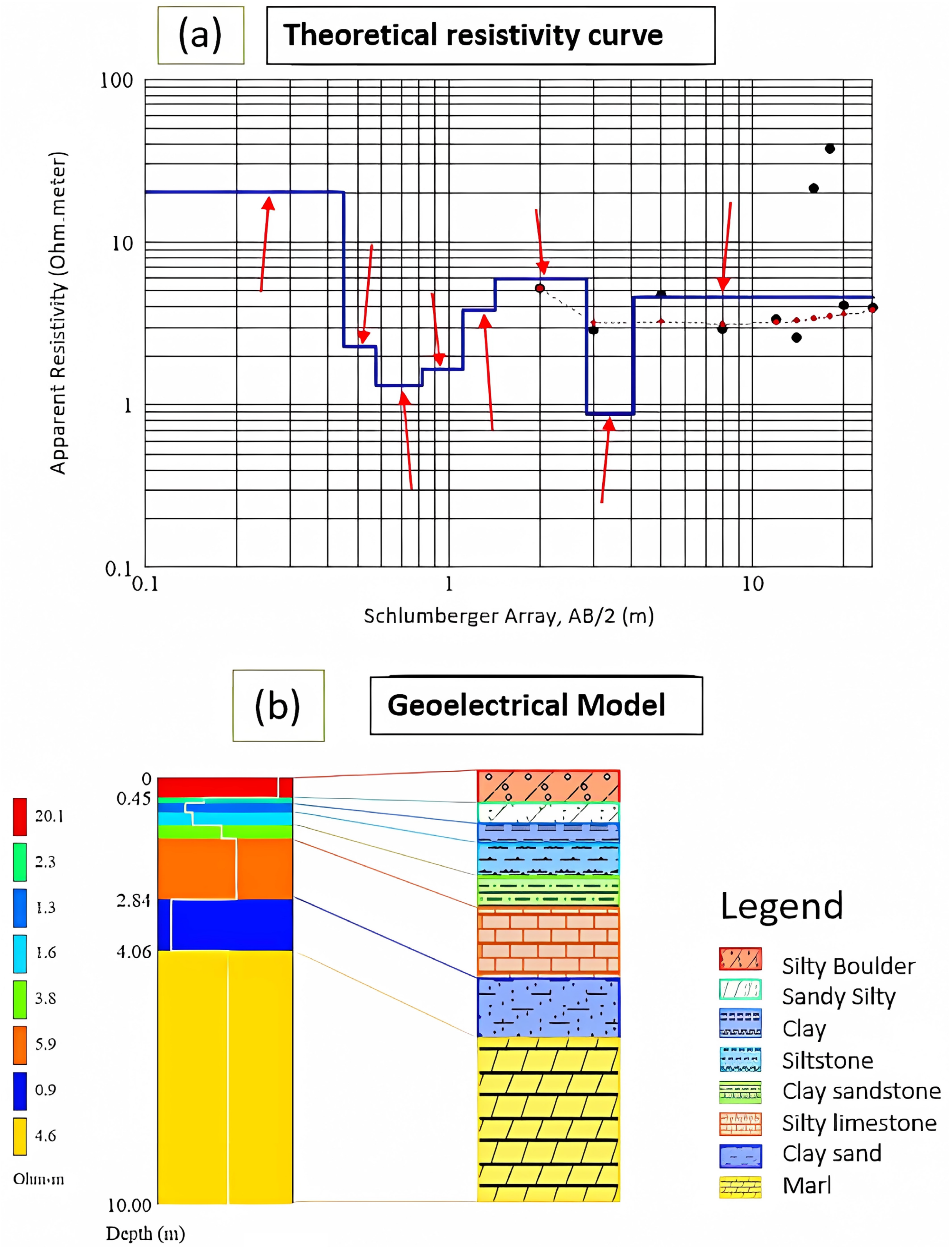

Figure 5. Theoretical resistivity curve and the 1D geoelectrical model. (a) Theoretical resistivity curve obtained by processing the data from the Vertical Electrical Sounding (VES). The red lines are the layers from the adjusted theoretical curve. (b) The geoelectrical model containing the layers, its depths and resistivity.

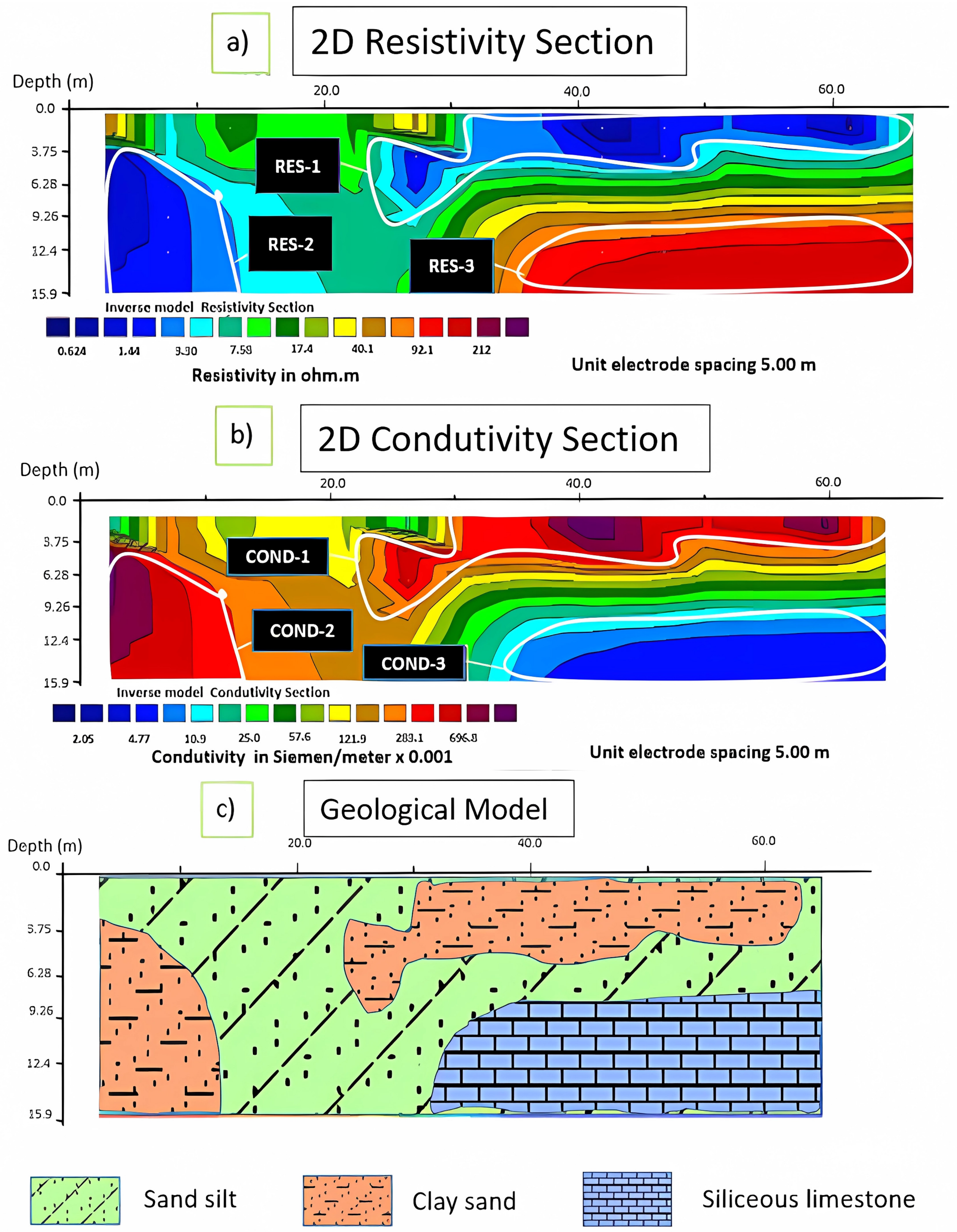

Figure 6. Resistivity and conductivity electrical sections from profile-11. (a) Resistivity electrical section; (b) Conductivity section; (c) Inferred geological model from the resistivity and conductivity values.

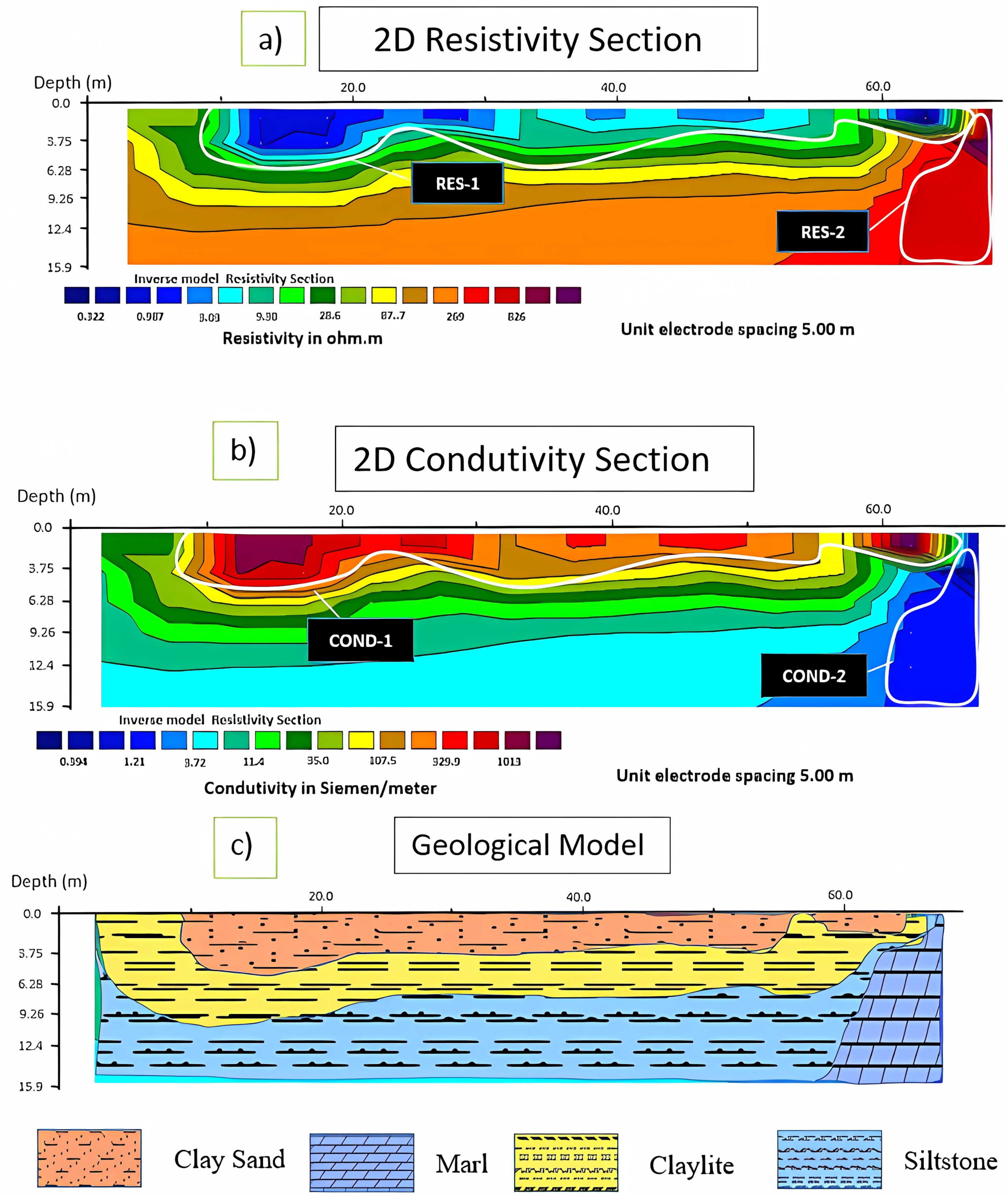

Figure 7. Resistivity and conductivity electrical sections from profile-22. (a) Resistivity section; (b) Conductivity section; (c) Inferred geoelectrical model from the resistivity and conductivity values.

resistivities. The same number of conductive areas is identified in profile-44 and profile-55, but with different values of resistivity or conductivity (**Figure 9** and

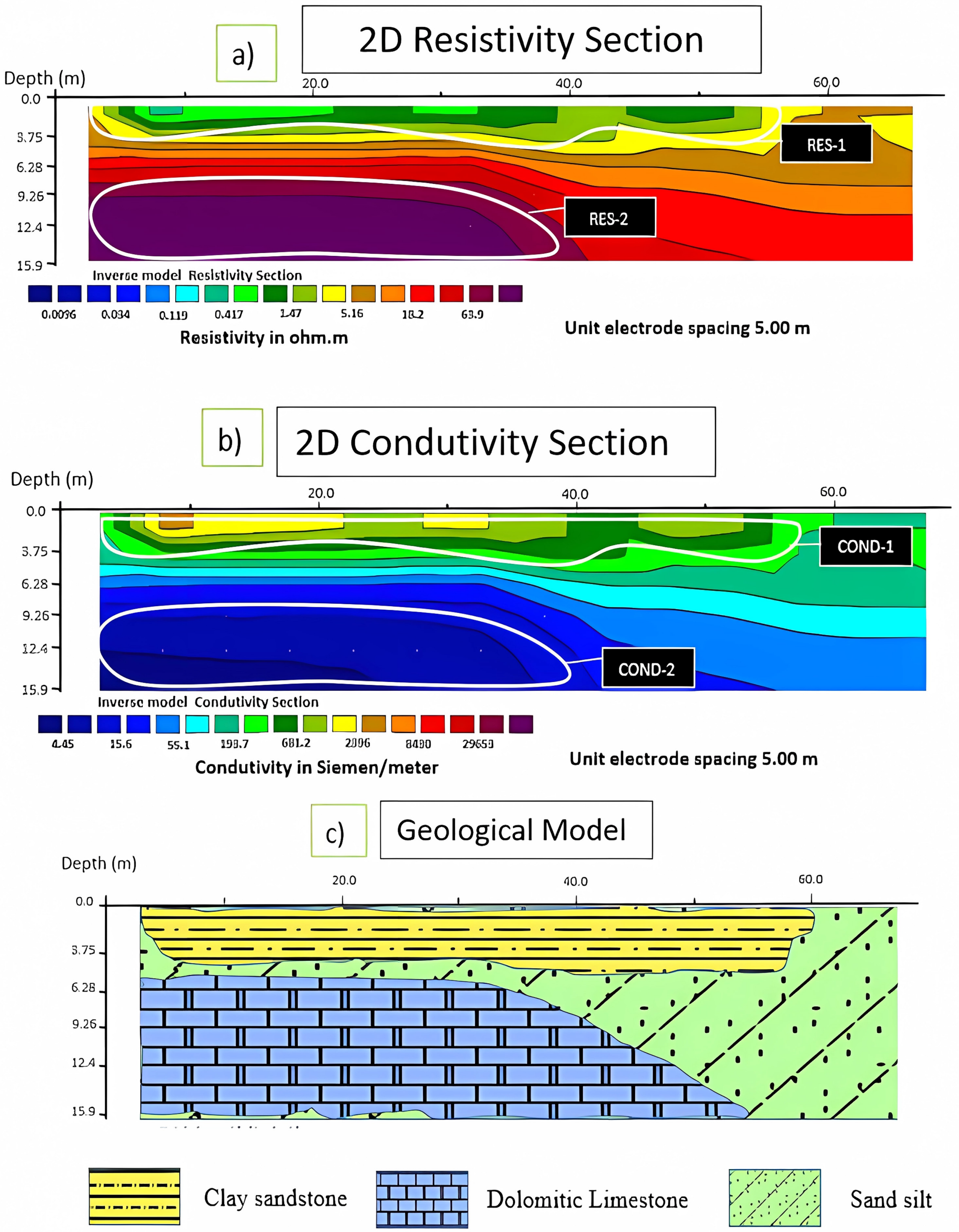

Figure 8. Resistivity and conductivity electrical sections from profile-33. (a) Resistivity section; (b) Conductivity section; (c) Inferred geoelectrical model from the resistivity and conductivity values.

Figure 10). In profile-44, the first area near surface show conductive values that vary from 0.10 - 1.20 S/m and second area vary from 0.0005 - 0.002 S/m. The two conductive areas were geologically interpreted as Siliceous shale for high resistivity, Silty boulder (near the surface) and Siltstones for low and intermediate resistivities. The last profile-55 the conductivities in these two areas vary from 0.28 - 3.12 S/m and 0.003 - 0.007 S/m. These areas were characterized as siliceous limestone for high resistivity, clay sands for low resistivity and siltstones the intermediate resistivity zones.

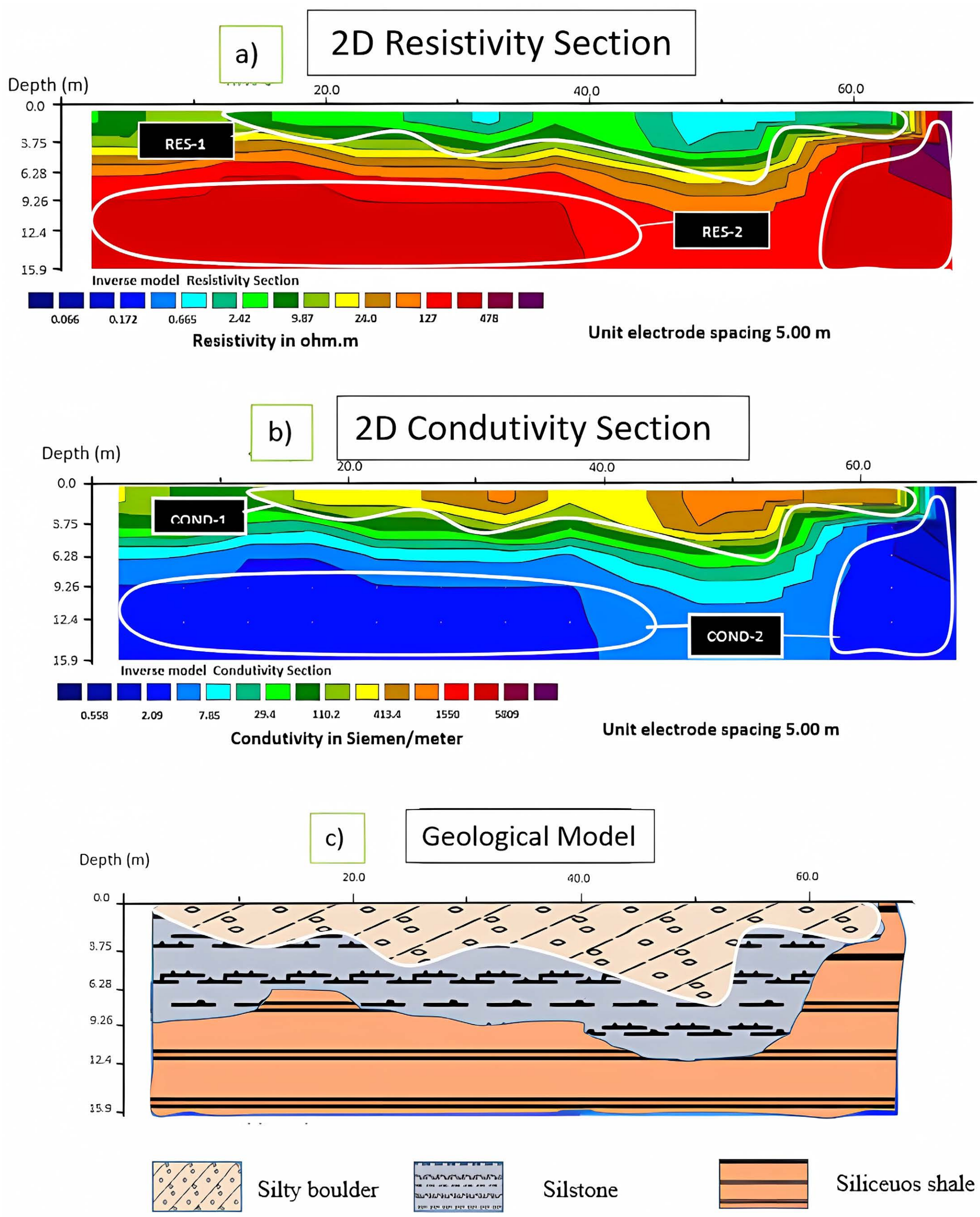

Figure 9. Resistivity and conductivity electrical sections from profile-44. (a) Resistivity section; (b) Conductivity section; (c) Inferred geoelectrical model from the resistivity and conductivity values.

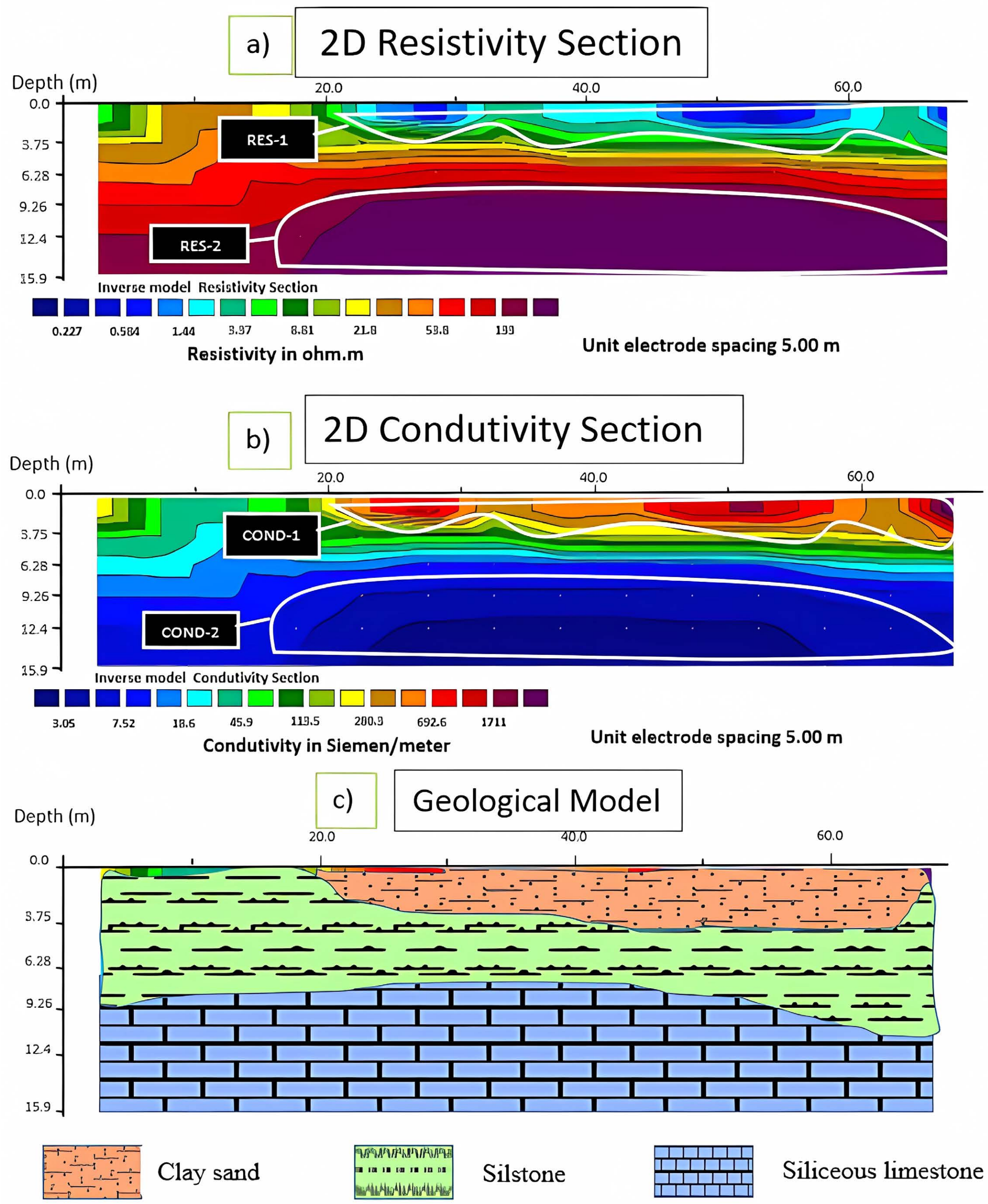

Figure 10. Resistivity and conductivity electrical sections from profile-55. (a) Resistivity section; (b) Conductivity section; (c) Inferred geoelectrical model from the resistivity and conductivity values.

The results from geoelectrical survey carried out in Kabiri town of Ícolo province show how the variations of resistivity are related to soil condition for coffee cultivation. These variations were divided into different zones or areas such as RES-1, RES-2 and RES-3. RES-1 zones have low resistivity and high conductivity that are associated with clays. This low resistivity in clays occurs because their particles provide in relation to the electrolytic path, an alternative path of low resistance that is based on the distribution of cations around these sediments. This scenario, through the analysis of the electrical sections in the study area, allows the clay thicknesses to be determined. In all 2D resistivity cross sections in the study area show that the clay sand layers (RES-1) have a thickness that range from 3.75 to 6.38 m.

With regards to the zones of RES-2 and RES-3, their resistivity values presented in the 2D geoelectrical sections are relatively high except for the 2D electrical sections from profile-11 which shows low values in the RES2 zone. The observed data in the RES-2, RES-3 zones and in the edge of these 2D geoelectrical sections are resistivity values that may present a high degree of uncertainty due to low density data of apparent resistivity measured during the acquisition and considering the electrode configuration used in this study [7]. As a result, the interpretations of these zones may be subject to errors due to this lack of resistivity data used for inversion and interpolation of the geoelectric sections. However, these zones are relatively 9 m deep and do not influence the purpose of this study, which focuses on the most superficial regions.

Table 3. Variation in soil conductivity in the area of interest for coffee cultivation.

2D Electrical Section	Soil conductivity (Siemen/meter) in the COND-1 region
Profile-11	0.30 - 1.60
Profile-22	0.25 - 0.25
Profile-33	0.19 - 2.39
Profile-44	0.11 - 1.20
Profile-55	0.28 - 3.12

Based on different scientific data and Ozegin 2022, the appropriate soil conditions for coffee cultivation have electrical resistivity values that vary between 10 and 100 Ω·m (0.1 and 1.0 S/m). However, for the study area due to the geological characteristics, the RES-1 zones that show low electrical resistivity values ranging approximately from 0.32 - 11 Ω·m are the most conductive and suitable areas for coffee cultivation (**Table 3**). The low resistivity values in these areas are characterized by organic soils, or soils with high water content with good drainage, which are the ideal conditions for growing coffee. Clay and organic soils are generally naturally rich in nutrients, so fertilization is usually necessary to ensure healthy plant growth. On the other hand, the geological layers and zones with higher electrical resistance interpreted as silty boulder, silty shales, clayey limestone and marls may also be suitable for coffee cultivation, but with some restrictions [4] [11]. Since these soils have less organic matter, poor drainage and low water-holding capacity, which can limit coffee growth, other factors like climate, altitude, and water availability must be taken into account before planting coffee.

Based on 2D resistivity cross section, geological map from Kabiri, we also propose the planting of crops and tubers such as potato, cassava, carrot, beetroot, lettuce, cabbage, spinach, beans, soybeans, peas, soybean, cotton, apples, bananas, oranges, mangoes, corn, wheat, rice, peas, clover, peanut.

5. Conclusions

The application of geoelectrical techniques using the resistivity and conductivity values from SEV and 2D resistivity cross section allowed to divide the study area into three different zones (RES-1, RES-2 and RES-3) according to their resistivity values. The RES-1 or COND-1 zones present in all near-surface geoelectrical profiles are areas that have potential for coffee cultivation with low resistivity values associated with clay sands. However, this method shows some limitations due to soil heterogeneity and data resolution such as:

1) The Wenner-Schlumberger array used may not have captured all the complexities of subsurface resistivity values, mainly in areas where soil properties vary significantly in short distances. This variation was not taken into account, but may have affected the resolution and interpretation of geoelectrical data.

2) The zones with low resistivity high conductivity values can not be naturally rich in nutrients, because soil nutrient content can vary for reasons not directly related to high soil conductivity. Therefore, the 2D geoelectrical sections need to be integrated into laboratory soil analysis studies and more additional geological studies using samples taken from wells.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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