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EXPLORATION OF CLAYS FOR CEMENT PRODUCTION USING 2D ELECTRICAL RESISTIVITY IMAGING, AND MINERALOGICAL AND GEOCHEMICAL EVALUATION IN BAZYAN AND TAKYA SITES, KURDISTAN REGION, NE IRAQ

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Abstract

Clay materials are widely used in the production of cement due to the presence of good amounts of silicon oxide (SiO_2), aluminum oxide (Al_2O_3), and ferric oxide (Fe_2O_3) that play an effective role in mixing with limestone to make Portland cement. However, exploring for good specifications of clay has become an important requirement for cement factories in general and in particular in both Bazyan and Takya regions due to the existence of more than five factories producing millions of tons from Sinjar Formation annually. Therefore, two sites were selected: site 1 in the Bazyan area near Kani-Shaya village and site 2 near Takya district. A 2D Electrical Resistivity Imaging (ERI) is conducted using the Wenner-Schlumberger array to detect clay layers in the Quaternary Sediments. Mineralogical and Geochemical studies are carried out to determine the quality of the detected clay layers. Thirteen clay samples were collected from different locations and depths depending on the results of the 2D ERI by digging 9 trenches to a depth of 12 m as well some other samples were collected in clay layers that appeared on several vertical cliffs of 7 – 10 m high. In addition, the 2D ERI profile identifies a cliff of about 9 m in height on clay layers. Geochemical analysis was carried out on seven clay samples to determine the major and minor element proportions. Six samples were analyzed to determine the grain size and mineral composition by XRD.

The results of the 2D ERI survey showed that there are large quantities of clay bodies in the Quaternary sediments at depths between 2 – 80 m with electrical resistivity ranging between 7 – 11 Ohm.m and the average thickness of the clay layer ranges between 5 – 45 m. The chemical composition analysis indicates the existence of a high ratio of silica, alumina, and iron oxide equal to 65.9 %, 11.66 %, and 4.4 % respectively in the Takya study area and equal to 33.58 – 37.63 %, 9.96 – 9.56 %, and 4.9 – 4.33 % respectively in the Bazyan study area. Grain

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size analysis shows that the majority is silt size, ranging from 48 to 58%, especially in the trenches, and then clay size ratio, ranging from 36 to 47%. The sand size in both study areas has the lowest ratio, ranging from 4% to 6%. The result is represented by silty clay and silty clay loam, according to the USDA diagram. Eventually, the mineralogical study indicates that the major portion of clay samples is montmorillonite, the minor portions are palygorskite and kaolinite, and the non-clay minerals include quartz, feldspar, and calcite. The result of the integrated studies is the detection of thick clay layers with optimal quality that can be used for several years as a raw material for the cement industry.

Keywords: 2D Electrical Resistivity Imaging; Clay raw material; Cement factory; Geochemical and grain size analyses.

1. Introduction

Portland cement is the most widely used kind of cement in the world as a fundamental component of concrete. Cement is made from a mixture of lime, silica, alumina, and iron oxide. After this mixture is pulverized and sintered, gypsum is added as a retardant (Murray, 2006).

Limestone is a common raw material in many industries and also the first raw material used in the cement-making industry because of its chemical properties. Limestone, as the main raw material, is mostly composed of the minerals calcite ($CaCO_3$) and dolomite ($Ca\,Mg\,(CO_3)_2$). They may also include other carbonate minerals and non-carbonate substances (Chatterjee, 2018). Also, clay, as a second raw material, is used as a main source of silica, alumina, and iron oxide (Abou El Leil & Al Faitory, 2023), and then, at around 1450 °C, in a rotary kiln, generates a calcium silicate clinker. In some cases, iron ore and sandstone are required, depending on the ratio of silica and iron oxide (Chatterjee, 2018), and eventually ground and combined with a small amount of gypsum (Bouazza, El Mrihi, & Maate, 2016). The chemical composition of Portland cement shall conform to the respective standard chemical requirements according to ASTM (2009), which is highly comparable to the chemical compositions of limestone and other raw materials, although limestone rock generally contains small quantities of other minerals, such as quartz (SiO_2), feldspar (alkali or lime silicate), clay minerals (hydrous aluminum silicates), pyrite (FeS_2), siderite ($FeCO_3$), etc., in the form of small dispersed particles) (Chatterjee, 2018). In general, the estimated burning behavior of a kiln feed is determined by considering into account the lime saturation factor (LSF), silica modulus (SM), or alumina modulus (AM) that is applied to clinker (Chatterjee, 2018).

Clay, or soil, is composed of clay minerals and non-clay minerals. The main clay minerals are kaolinite, smectites, illite, and chlorite, which consist of silicon, aluminum, oxygen, and hydroxyl ions. The non-clay minerals are generally composed of quartz and calcite (Murray, 2006). Obviously, clay minerals affect cement properties, such as montmorillonite, which decreases the setting time, and kaolinite, which adds strength to the cement (Zhou, et al., 2022).

2D electrical resistivity imaging (ERI) is used in this study to explore the clay sediments in Bazyan and Takya sites, NE Iraq. The ERI is performed by measuring the voltage difference that occurs between two potential electrodes when a current is passed through two current electrodes. Pseudo-section profiles of the subsurface are produced by ERI via recorded apparent resistivity values. Where the four electrodes are arranged or distributed influences the sensitivity, resolution, and noise incorporation of each apparent resistivity measurement. Resistivity values can be obtained by using an iterative numerical inversion of the apparent resistivity (Smith & Sjogren, 2006). Furthermore, laboratory assessments and geological surveys are required because the mineral and chemical composition of the raw material highly affect the properties of the cement composite (Murray, 2006; Nehdi, 2014; Fatah, Ahmad, & Mirza, 2020; Sissakian, et al., 2021). Additionally, geological surveys are carried out to evaluate the quantity of clay raw material. In the Bazyan area, depending on the existence of the Tertiary Sinjar limestone Formation, five high-capacity factories are producing cement, which also requires a high amount of clay. This research aims to identify potential, suitable clay resources.

2. Location and geological setting

The study area includes two sites. Site 1 is located within Sulaimani-Bazyan governorate near the limestone quarry of the Sinjar Formation (Late Paleocene – Miocene) and Kani-Shaya village of Bazyan basin, which is located nearly 25 Km west of Sulaimni city at the intersection point of latitude 35°32'46''N and longitude 45°11'54''E, as shown in Figures 1 and 2. The Bazyan Basin is a nearly flat agricultural area intersected by several U-shaped valleys that have dendritic and parallel drainage patterns, such as the Warmzyar and Bazyan valleys. The thickness of alluvial sediments (Quaternary Sediments) differs from one place to another and is mostly composed of clays with gravels, sands, and silts as horizons extending laterally and vertically. Tectonically, from west and south-west, the basin is bordered by high-altitude mountains of the Hanjira and Bazyan Series, which represent the natural series belt separating the Low Folded Zone from the High Folded Zone, where the site is located within the High Folded Zone (Buday & Jassim, 1987). The site 2 lies in the Takya district within the Sulaimani – Chamchamal Governorate near the claystone quarry of the U. Miocene Injana Formation, which is used for the brick industry at the intersection point of latitude 35°36'14''N and longitude 44°56'28''E, as shown in Figure 1. From a tectonic point of view, it is located within the Low Folded Zone (Buday & Jassim, 1987). The Low Folded Zone is distinguished by numerous topographic characteristics that reflect the type of exposed rocks, their thicknesses, and their structural effects. In general, two separate topographical forms were identified according to the existence of longitudinal narrow anticlines and wide synclines (Sissakian & Al-Jibouri, 2012). In the studied area, a very thick Quaternary Sediment of about 9 m appears and covers the Injana Formation, as shown in Figure 1. The Injana Formation is characterized by highly compacted sandstone, siltstone, and claystone alternation (Al-Juboury, 2009).

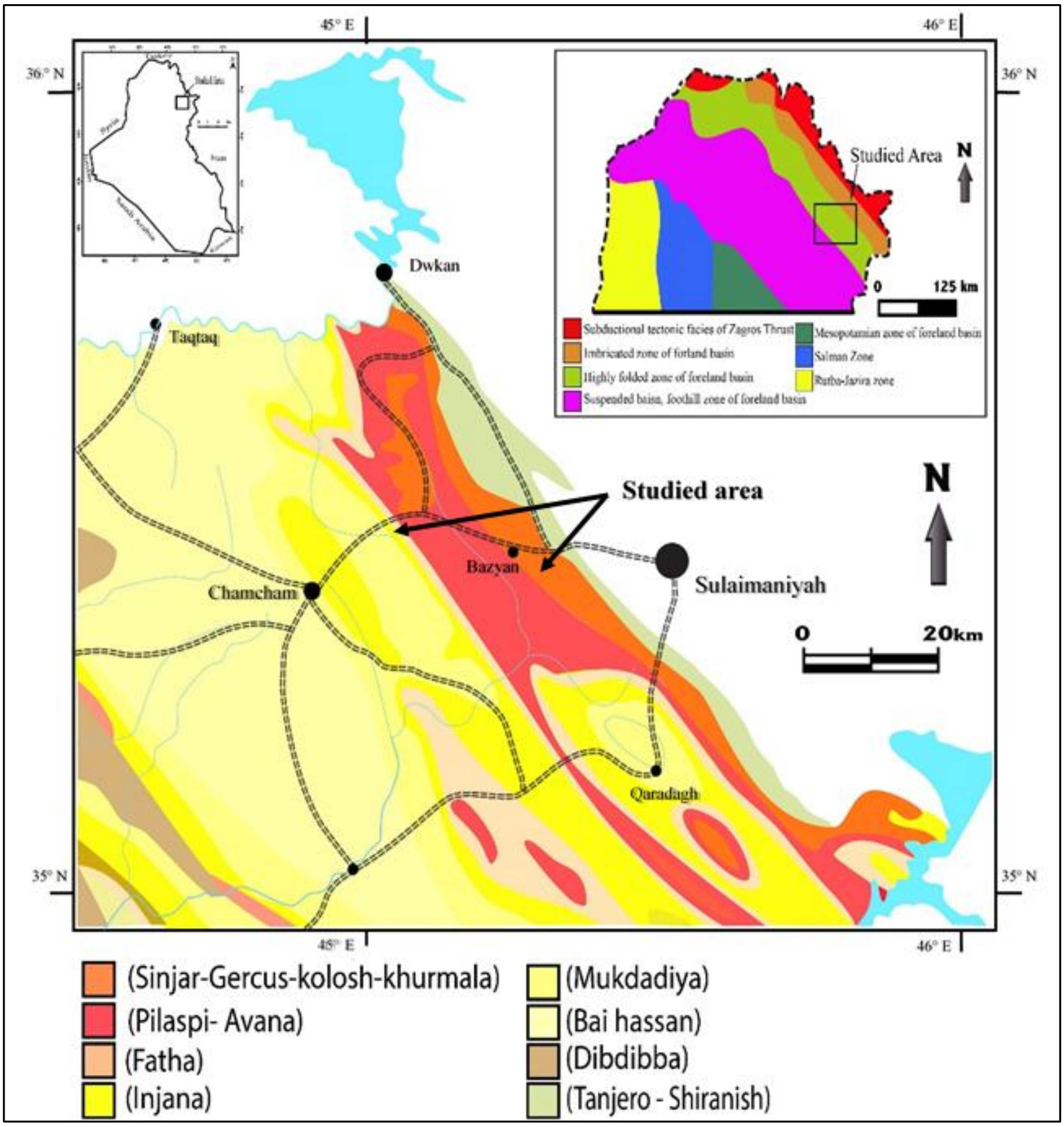

Figure 1. Geological map of the studied area after Sissakian (2000). The index maps in the upper left and upper right show the location of the study area relative to the Iraq map and relative to the tectonic divisions of Iraq, respectively.

3. Methodology

Geological surveys and laboratory tests were carried out at the two sites. Site 1 in Kani Shaya, near the Bazyan area, is composed of nine trenches. Figure 2a displays a field photo of one of these trenches, which are used for evaluating mineral composition, grain size analysis, and chemical composition. The trench's depth ranges from 5 to 6.5 m. Six samples of clay were collected: two for chemical analysis depending on the variation of physical and organic material content, two for mineralogical study, and two for grain size analysis. Site 2 is composed of a cliff 5 – 9 m high near Takya District, (Figure 2b). Three samples were collected for the assessment of grain size analysis, mineral composition, and chemical composition. Furthermore, ERI is carried out for both sites. The acquired resistivity data were processed and inverted to 2D ERI by utilizing Geotomo Software that commercialized the RES2DINV program (Loke, 2004). A Wenner–Schlumberger array was used with two different electrode spacing equal to 5m and 10m. The chemical analysis by X-ray fluorescence (XRF) was carried out in the Central Laboratory Department of the Iraq Geological Survey and the research laboratory of the Geology Department at the University of Soran. Particle size distribution based on American Standard Test Method D422-63 (ASTM D.-6. , 2002) was measured in the Aso Brick Factory lab. The mineral constituents (XRD) were determined in the Central Laboratory Department of the Iraqi Geological Survey and the research laboratory of the Geology Department at the University of Soran. Clay fractions of samples are separated according to Moore & Reynold (1997) for XRD analysis by digesting sample powder with HCl to remove carbonate fractions, H_2O_2 to remove organic matter, and Na-Hexametaphosphate to disperse and separate clay particles.

Figure 2. Field photos showing a trench (a) and a cliff (b) in the study area. Note the luster of the clay layer in the trench that reflects the good quality and the considerable thickness of clays in both photos.

4. Results and Discussion

The Quaternary (recent) Sediment in the Bazyan area (site 1) that overlies the Kolosh Formation is generally divided into three zones: the top is organic soil that is characterized by brown color, friability, presence of vegetation roots, porousness, and few carbonate fragments. In the middle is clay and compacted clay that is differentiated by a light brown color, being slightly compacted, the presence of carbonate fragments, and being silty. At the bottom is compacted clay, which is distinguished by brown to light-brown colors, highly compacted and silty, and has very few carbonate fragments. In the Takya area (site 2), recent sediments overlie the Injana Formation and it is also divided into three zones: the top is organic soil that is characterized by a dark brown color, the presence of vegetation roots, and a few carbonate fragments. In the middle is a clay differentiated by its brown color compactness, and high presence of carbonate fragments. At the bottom is claystone, distinguished by its reddish-brown color, highly compacted, and has very few carbonate fragments.

The average chemical analyses of the three samples; two from trench no.1 and 7 and the other one from the cliff, are shown in Table (1). The analyses show an acceptable ratio of SiO_2, Al_2O_3, and Fe_2O_3 from the two trenches as well as a high amount of SiO_2 from the cliff. Fundamentally, these ratios are compared to the silica modulus (SM) or alumina modulus (AM) of clinker, which should be equal to 2.4 ± 0.2 and 1.4 ± 0.2, respectively, according to (Chatterjee, 2018). Also, the high ratio of CaO in the trenches should be taken into consideration when mixing with detrital and marly limestone that has a low CaO content, thereby equalizing the standard level depending on the lime ratio of the raw-mixed materials, and the lime saturation factor (LSF), which is considered the optimal range equal to 1.0 ± 0.05 (Chatterjee, 2018). Three samples were collected for grain size analysis. Two samples in trench numbers 5 and 8, while the third one was collected from the cliff. These showed that the major component of the samples is silt, followed by clay and sand, as shown in Table (2). Therefore, according to the USDA analysis diagram (García-Gaines & Frankenstein, 2015). The raw materials in trench 5 and the cliff are classified as silty clay, and in trench 8 as silty clay loam, as shown in Figure 3.

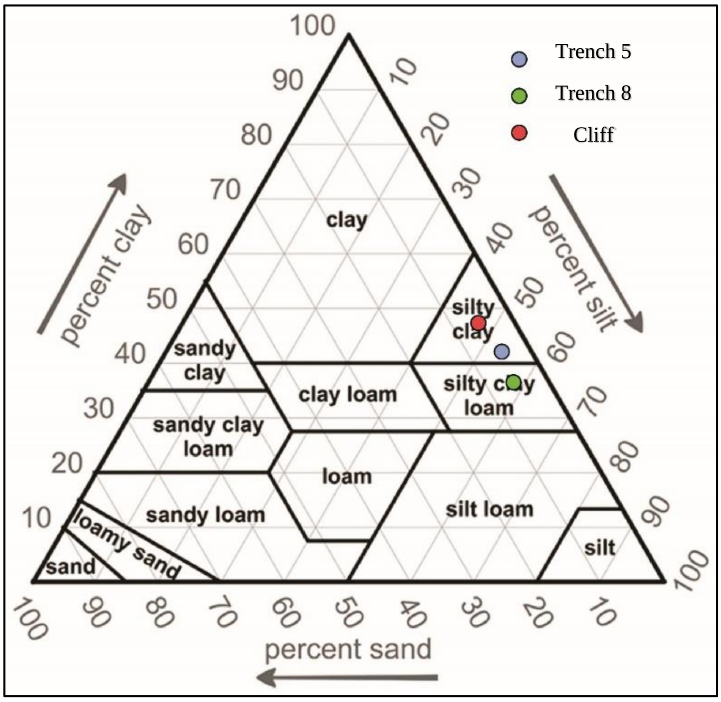

Figure 3. Determination of soil classification of the studied sample on the USDA diagram (García-Gaines & Frankenstein, 2015).

Table 1. Results of chemical analysis of the studied samples.

Sample	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	CaO %	MgO %	SO_3 %	Na_2O %	K_2O %	CL %
Trench 1	33.58	9.56	4.33	24.26	3.68	<0.07	0.453	0.91	0.086
Trench 7	37.63	9.96	4.9	20.11	3.96	<0.07	0.513	1.206	0.07
Cliff	65.9	11.66	4.4	10.86	5.26	0.216	-	1.316	-

Table 2. Results of the grain size analysis of the studied samples.

Samples	Sand%	Silt%	Clay %
Trench 5	4	54	**42**
Trench 8	6	58	**36**
Cliff	5	48	**47**

The result of mineralogical analysis using X-ray diffraction is shown in Table (3) for three samples of soil and clay which are collected from trenches 1, 7, and the cliff of the study area. In the trenches, calcite is most common, quartz and feldspar are less common and epitomize non-clay minerals, while montmorillonite is most common, and palygorskite and kaolinite are less common and epitomize clay minerals as shown in Figure 4. The X-ray diffraction pattern for the studied samples in the cliff near the Takya area shows that the clay minerals are montmorillonite and kaolinite, and the non-clay minerals are calcite and quartz as shown in Figure 5.

Table 3. Result of the mineral composition analysis of three studied samples (from trenches 1 and 7 and the cliff).

Samples	Clay Minerals			Non- Clay Minerals		
Trench 1	Montmorillonite	Palygorskite	Kaolinite	Quartz	Calcite	**Feldspar**
Trench 7	Montmorillonite	Kaolinite	-	Quartz	Calcite	**Feldspar**
Cliff	Montmorillonite	Kaolinite	-	Quartz	Calcite	**-**

The Bazyan area is one of the most important agricultural areas in Sulaymaniyah Governorate because of the large number of greenhouse projects, forests, and other kinds of agricultural activities (Rahman, Tawfiq, Amin, Abdullah, & Abdullah, 2020). It contains several shallow and deep underground aquifers (Aziz B. Q., 2005) and impermeable layers of claystone layer from the geological formation (Buday & Jassim, 1987). Chamchamal Plain, only in the southwest part of the area, is the most favorable for groundwater existence. While low groundwater potential zones characterize the central and northeastern parts, also they are considered semi-arid conditions (Mohammed, Mohammed, & Szűcs, 2021). Therefore, selecting clay as a raw material for the Portland cement industry near the Takya area of Chamchamal district is more appropriate.

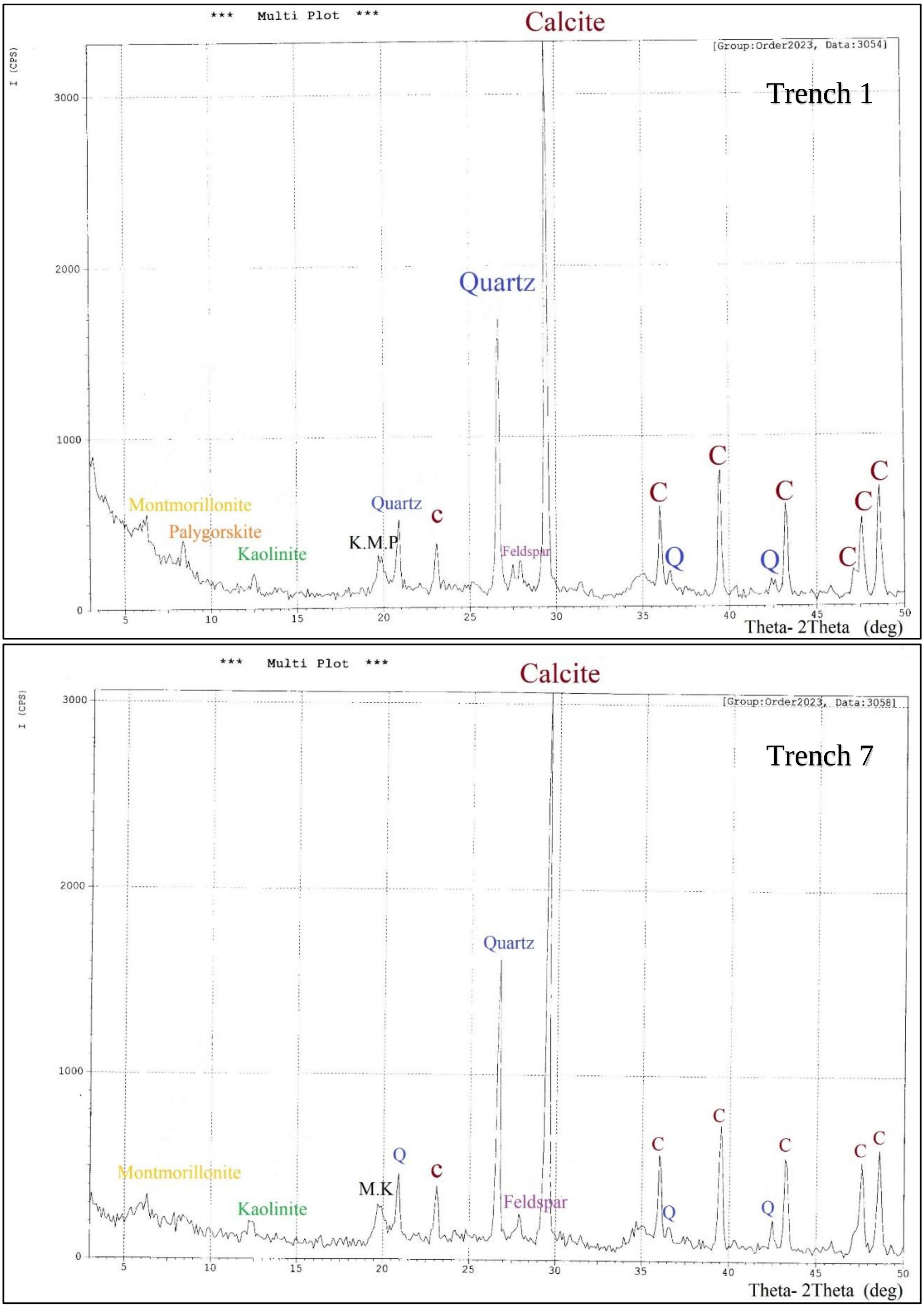

Figure 4. X-ray diffraction pattern for studied samples in Trench 1 and 7 near Bazyan area.

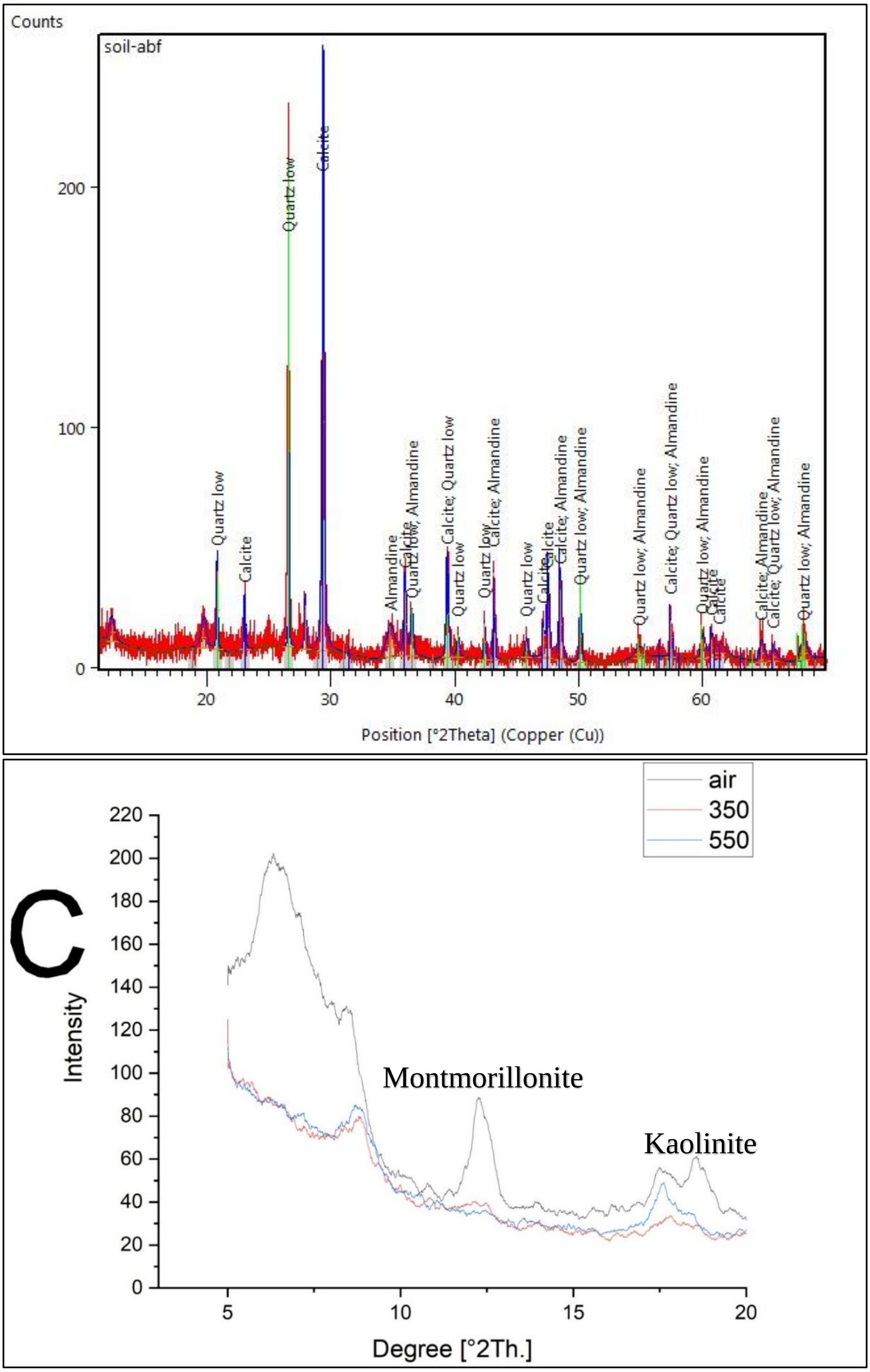

Figure 5. X-ray diffraction pattern for studied samples in the cliff near the Takya area.

4.1. 2D ERI of the Study Area

The data is interpreted by using the latest version of the RES2DINV program (version 4.10.20, 2020) (Prosys III). The 2D resistivity sections showed a smooth inversion with good quality, and the bad data were removed manually before the inversion process. The locations of the 2D resistivity section are identified on the Google map as shown in Figure 6.

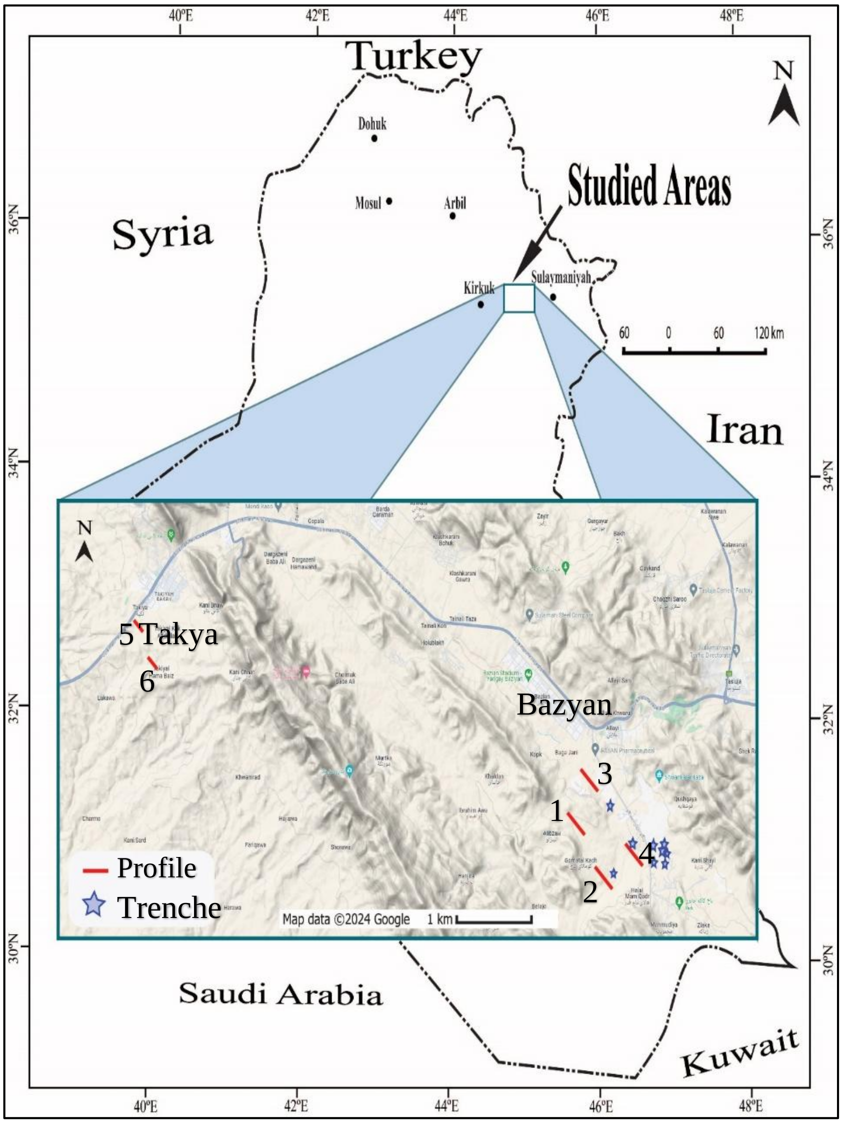

Figure 6. Google Maps, which indicates the location of the profiles. The index maps show the location of the study areas relative to the Iraq map.

4.1.1. Profile-1 (710 m length, electrode spacing is 10 m)

This profile is conducted in the Bazyan area, running approximately parallel to the strike of the outcrops; measured and calculated apparent resistivity sections show very smooth and good-quality data, as shown in Figure 7.

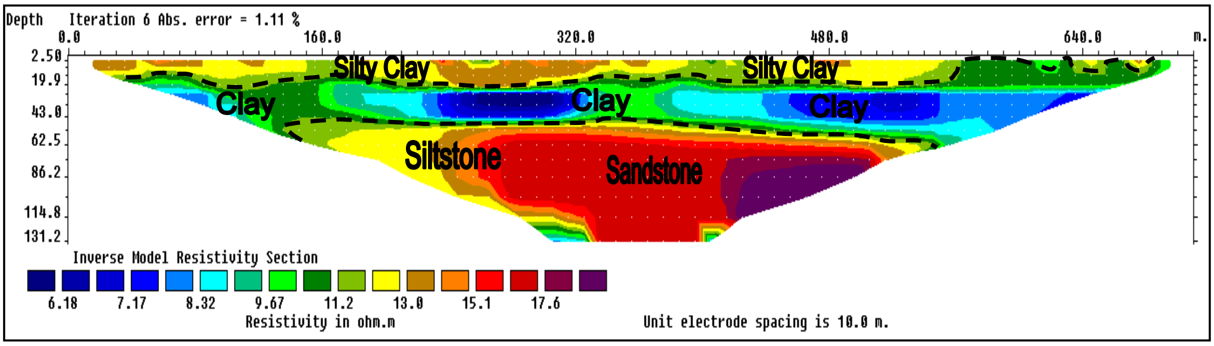

Figure 7. Interpretation of profile -1 in the Bazyan area.

The first layer (has yellow and brownish color) and is of moderate resistivity ranging from 12 to 15 Ohm.m It represents the top surface layer composed mainly of clay and silt of the recent sediments derived from weathering and erosion process of the Sinjar, Gercus and Kolosh Formations. The thickness of this layer ranges from 2 to 19 m. It is composed of clay and silt.

The second layer is represented by the blue color of low resistivity with respect to the above layers. It is composed of claystone and it shows a resistivity range from 7 to 10 Ohm.m. It has a thickness ranging from 23 to 41 m.

The third layer (reddish color) represents the coarse grains cycle of the Recent sediments, composed mainly of siltstone and sandstone. It shows a high resistivity range, from 15 to 40 Ohm.m and it is detected at depths ranging from 45 to 55 m.

4.1.2. Profile-2 (710 m length, electrode spacing is 10 m)

This profile is conducted in the Bazyan area, and the quality of recorded data is good, as shown in Figure 8. A top layer of coarse materials has high resistivity ranging from 10 to 16 Ohm.m and covers the surface of the area. It is composed of silty clay and has a thickness ranging from 3 m to 19 m.

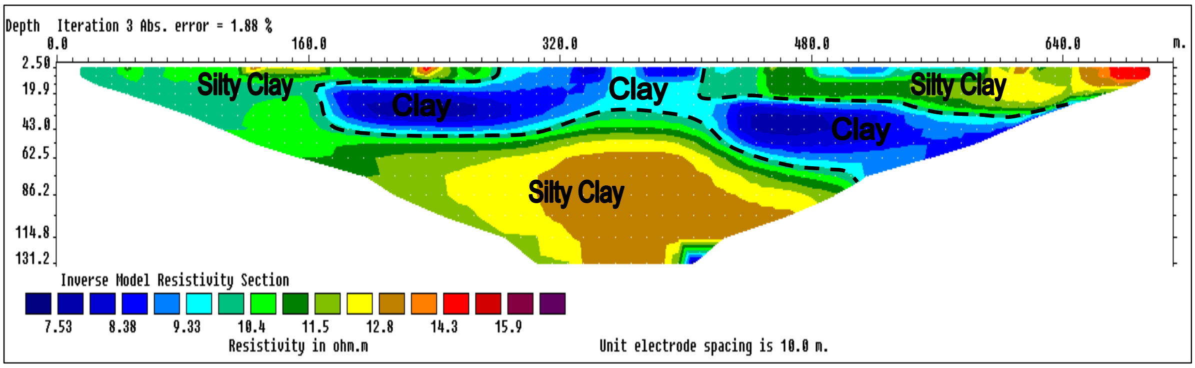

Figure 8. Interpretation of profile -2 in Bazyan area.

A thick layer of clay cropped out beneath electrodes 30 to 43 which is represented by a blue color, has resistivity ranging from 7 – 10 Ohm.m. The thickness of the clay layer ranges from 18 to 45 m. Beneath the clay layer, coarse grain cycles of Recent sediments, composed mainly of siltstone appeared. It shows high resistivity ranging from 11 – 13 Ohm.m and it extends from 45 m to the maximum depth of investigation equal to 131 m.

4.1.3. Profile -3 (710 m length, electrode spacing is 10 m)

The profile was executed in the Bazyan area; it runs approximately parallel to the strike of the outcrops. Measured and calculated apparent resistivity sections show very smooth and good-quality data, the final interpretation is shown in Figure 9. Three layers have been identified; the first layer (in light blue) is of moderate resistivity ranging from 11 to 16 Ohm.m. It represents the soil cover and is composed mainly of clay and silt of Recent sediments derived from weathering and erosion processes on the Sinjar, Gercus, and Kolosh Formations which crop out adjacent to the study area. The thickness of this layer ranges from 2 to 17 m.

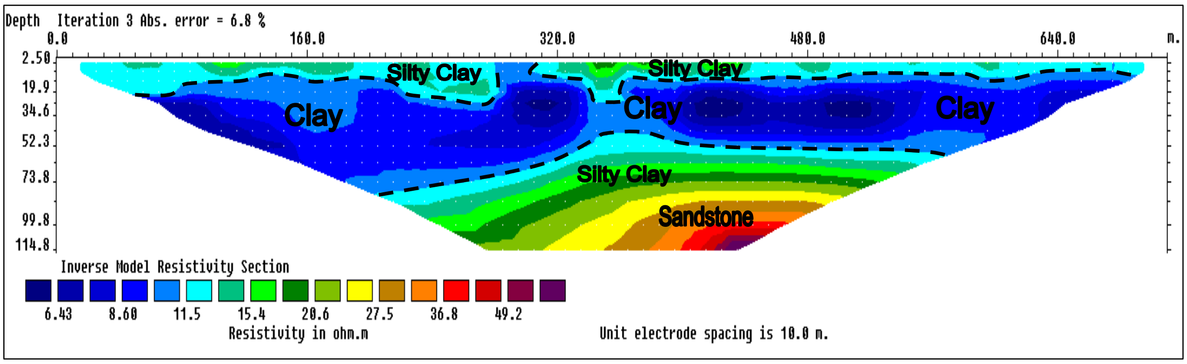

Figure 9. Interpretation of profile -3 in Bazyan area.

The second layer is represented by the blue color indicating low resistivity with respect to the above layers. It is composed of clay and clay stone and shows a resistivity range from 6.5 to 10 Ohm.m. It has a large thickness ranging from 15 to 50 m.

The underlain third layer (green and reddish colors) represents the coarse grains cycle of Recent sediments, which is composed mainly of siltstone at the upper part and sandstone at the lower part. It shows a wide range of resistivity ranging from 12 to 70 Ohm.m and it is detected at depths ranging from 50 to 90 m.

4.1.4. Profile -4 (710 m length, electrode spacing is 10 m)

It is located near Kany Shaya Village in the Bazyan area, executed over a flat area. It displays very good quality data except for the occurrence of a few high resistivity spots, attenuated by smoothing during apparent resistivity calculation. The final interpretation results are displayed in Figure 9. The apparent resistivity ranges between 6.5 – 60 ohm.m and it denotes the presence of Recent sediments from the upper part of the inverted section (Figure 10). This range is also obtained for the Recent sediments from the previous studies in Tainal town (Aziz B. Q., 2005).

The pure clay layer is cropped out covering the whole surface of the area equal to 710 m, Figure 9. The thickness of this layer ranges from 2 m beneath electrode 1 to 40 m beneath electrode 49. The interface between clay and coarse materials is selected at the boundary where the resistivity equals 13.5 ohm.m depending on the previous study (Aziz B. Q., 2005). It denotes to gradual increases of coarse materials to the deeper part of the section. The red color has a resistivity range from 45 – 110 ohm.m and represents a zone of more gravel content (highly saturated with groundwater). At the depth of 110 m gradually the resistivity decreases (shale content increases), this most probably denotes the appearance of the Kolosh Formation as indicated in the lower part of the inverted section by the blue color.

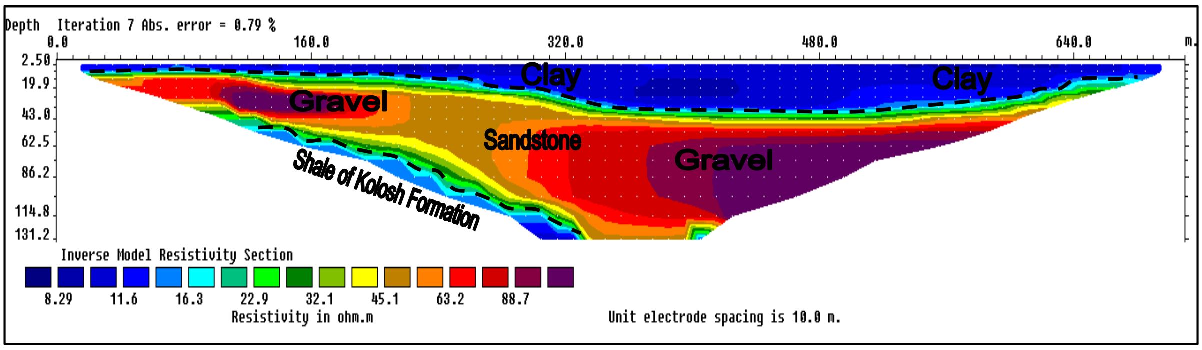

Figure 10. Interpretation of profile -4 in Bazyan area.

4.1.5. Profile -5 (355m length, electrode spacing is 5m)

This profile is selected in an area that lies south of Takya District where the Recent sediment covered the Injana Formation. It has an NW-SE direction. The ERI indicates a resistivity ranging from 9.46 Ω.m at the top layer to 24.7 Ω.m at the bottom generally divides the sections into two different zones. It also demonstrates that fine-grain materials such as clay and silt are present in the uppermost part of the sections, shown in blue color in Figure 11. A dashed black line separates the suitable claystone and silty claystone layers in the inverted section, with the resistivity ranging between 10.46 and 12.4 Ω.m which was determined as clay and silty clay according to (Hamaamin & Aziz, 2023). The figure also shows that the thin high-resistivity layers, such as clayey siltstone, sandy siltstone, siltstone, silty sandstone, and sandstone, are located in the lower part of the section, which is approximately 7 m thick. The depth of the investigation is approximately 34 m and the thickness of the claystone and silty claystone layers is about 25 m.

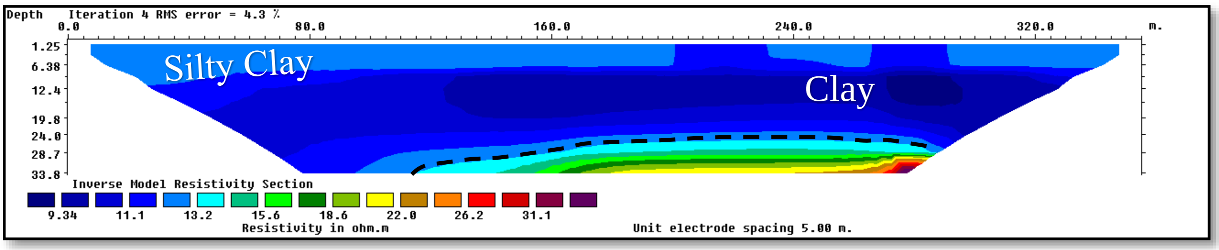

Figure 11. Interpretation of profile -5 in the Takya area.

4.1.6. Profile -6 (355 m length, electrode spacing is 5 m)

Profile-6 is located in the south of Takya District, where the Injana Formation is exposed on the surface and covered by Recent sediments. The trend of the profiles is SW-NE. The inverted resistivity section shows a resistivity varied from top to bottom of this layer, 11.3 Ω.m – 21.7 Ω.m, respectively, as shown in Figure 11. The dashed black line separates between silty claystone layers of resistivity ranges between 11.3 and 13.6 Ω.m (appears in blue) at the top and a very thick clayey siltstone layer (appears in green color), at the bottom. The thickness of the target layer (silty claystone) increases on both sides of the sections (Figure 12). The depth of the investigation is approximately 34 m. The target layer is exposed on the surface and considered a low cost for excavating with a considerable quantity of raw material.

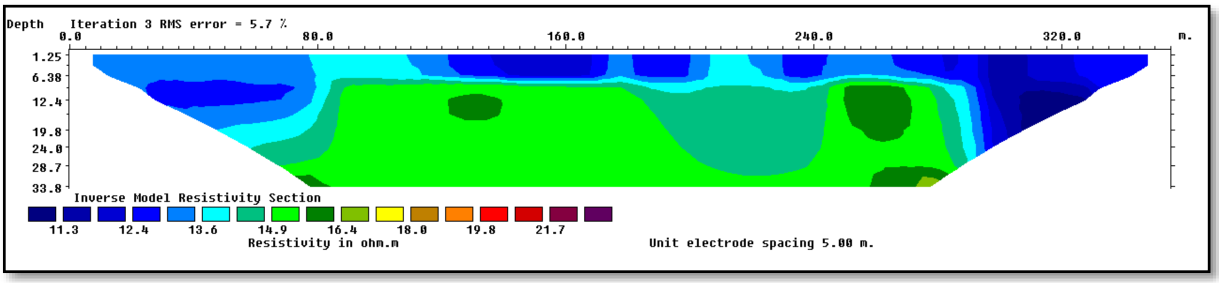

Figure 12. Interpretation of profile-6 in the Takya area.

6. Conclusions

Recently, the deficiency of raw materials for the cement industry has appeared in the Bazyan area, which has five high-capacity cement factories and is mostly used for agricultural purposes. Consequently, geophysical, chemical, physical, and mineralogical parameter studies were carried out to evaluate raw materials' best quantity and quality. The Electrical resistivity imaging (ERI) survey is a powerful tool for indicating the boundary of clay layers within Quaternary Sediments due to its low resistivity with respect to other components. The resistivity of the clay materials ranged from 6.5 to 10 Ohm.m and silty clay ranged from 11.3 to 13.6 Ohm.m throughout the whole area under consideration.

It is concluded presence of very thick clay layers within Quaternary Sediments. The average thickness of the detected clay layers is about 35 m with a lateral extension of 710 m. The clay layers are detected on the surface of the areas and extend to a depth equal to 90 meters. This is a huge quantity that can be used by cement factories for several decades.

It is found that the major sediments of the samples are silt size, ranging from 48 to 58%, especially in the trenches, with the clay size ratio as the second component ranging from 36 to 47% and is higher in the cliff than in the trenches.
The chemical composition indicates that the clay layer in both sites is used as a raw material for cement manufacturing because it contains a high ratio of silica, alumina, and iron oxide. For

the Portland cement industry, clay is the main source of these components, especially in the clay near the Takya area, which has a higher silica and alumina ratio. However, the clay near the Bazyan area, which has higher calcium oxides, should be taken into account concerning other raw material components.

Mineralogical analysis shows that montmorillonite is the main clay mineral followed by palygorskite and kaolinite. The non-clay minerals are quartz, feldspar, and calcite.

The integrated studies of the ERI, grain size analysis, chemical composition, and mineralogical analyses indicate that the detected thick clay layers are very suitable for the cement industry.

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