Contribution of Electrical Resistivity Tomography (ERT) and Vertical Electrical Sounding (VES) to delineate the structural organization of the Palaeozoic Zone in the Rabat-Tiflet region (Morocco)

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Abstract: In this geophysical study, we carried out four Electrical Resistivity Tomography (ERT) profiles and one Vertical Electrical Sounding (VES) in the Palaeozoic Zone in the Rabat-Tiflet region, Morocco. Measurements were accomplished in and around the limestone quarry exploited by the company named 'Société Des Granulats de Tiflet' (SDGT) located in our study area. The aim of this study is to delineate the structural organization, especially the spatial distribution of limestone deposits which represents the main formations of this Palaeozoic zone in the Rabat-Tiflet region. Analysis of 2D inverse model resistivity sections show some anomalous contacts and the existence of subsurface lenticular bodies with resistivity going from 100 to 1500 Ωm, potentially corresponding to limestone rock. Also, vertical electrical sounding achieving near the SDGT showed a layer with a resistivity of 317 Ωm at 6 m depth interpreted as limestone conglomerates or limestone deposits. More, during our geological survey, we observed along the Oued Bou Regreg valley and in some abandoned quarries located in the same area, lenticular blocks with different sizes globally having an NNW–SSE direction. These results contributed, even in small scall, to clarify the structural organization of the Palaeozoic Zone in the Rabat-Tiflet region. To map out with high precision this geological complex region, more electrical and seismic profiles as well geochemical studies are recommended.

Key words: Electrical Resistivity Tomography (ERT), Vertical Electrical Sounding (VES), Palaeozoic Zone in the Rabat-Tiflet region, 2D inverse model resistivity

1. Introduction

Massive limestone layers are considered as valuable natural resources for industrial development of a country, this material can be used in civil en-

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gineering projects with different forms: pulverized stones, calcined stones with production of quicklime (CaO), chopped stones (extracted from quarries and cut for construction) and crushed stones aggregates (*Keith and Webb, 2015*). In Morocco, limestone blocks are used frequently as ornamental rocks, located mainly in central of Morocco, along the Bou-Acila marbles deposits. Many studies have been conducted to characterize these exploitable materials (*Ouali and Ajakane, 2015; Lghoul et al., 2011; Jilali et al., 2015; Azizi et al., 2018*). In the Rabat-Tiflet region, limestone deposits have Paleozoic age, they were subject to various controversies according to their age, structural organization, and location (*Piqué, 1981; Lakhloufi, 2002; Mehdioui et al., 2020; Becker and El Hassani, 2020*).

Geophysical techniques are very useful for characterizing and mapping subsurface features since they are non-destructive, low cost and fast methods. They are considered useful and effective in many applications, such as studying groundwater quality and saltwater intrusion in coastal aquifers (*Singh et al., 2022; 2021; Swileam et al., 2019; Kumar et al., 2020*), understanding internal landslide structures and identifying areas at increased risk of instability (*Mondal et al., 2008*), determining geological formations and hydrogeological properties (*Gautam and Biswas, 2016*), or detecting waste along geological bodies like along the Moroccan phosphate deposits (*El Assel et al., 2011*).

This study aims to use of Electrical Resistivity Tomography (ERT) and Vertical Electrical Sounding (VES) in order to clarify the structural organization of the Paleozoic Zone in the Rabat-Tiflet region (PZRT in Morocco). Stratigraphy, this Paleozoic zone is made by Ordovician, Silurian, and Devonian deposits essentially limestone rocks (*Becker and El Hassani, 2020*). Electrical resistivity data were collected along four section profiles and then inverted in order to obtain the spatial distribution of the true resistivity values for different subsurface layers. The dipole-dipole electrode array was chosen because it is suitable for shallow formations and can cover a fairly large surface area (*Loke, 2001* and *2011*).

2. Study area

The study area is located in the Paleozoic zone of the Rabat-Tiflet region which represents the NW part of western Meseta, Morocco (Fig. 1A). It includes three main geological units: the Sehoul block sited in the north, the Bouregreg anticline in the centre, and the Sidi Bettache basin in the south (Fig. 1B).

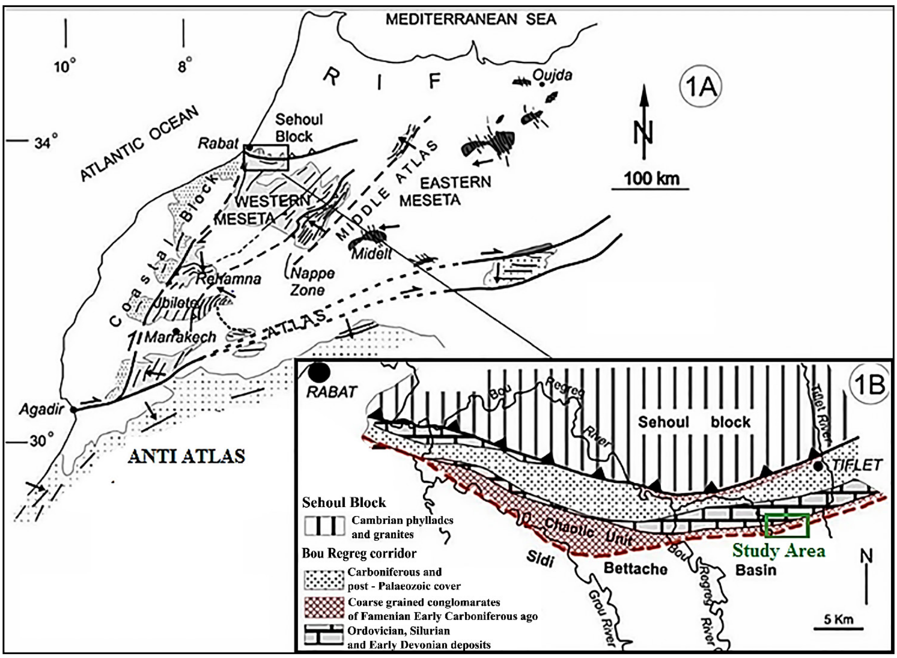

Fig. 1. Map showing the study area. 1A: Principal structural domains in Morocco. 1B: Main units of the Palaeozoic Zone in the Rabat-Tiflet region (after *Tahiri et al., 2010*).

Geologically, the Sehoul block is mainly composed of Cambrian phyllades and granites rocks related to the Caledonian orogeny in Morocco (*El Hassani, 1990; Piqué et al., 1993*). It is characterized by about 500 m thick deltaic series dated Cambro-Ordovician and affected by isoclinal metamorphic folds (*Piqué, 1979; El Hassani et al., 1991*).

The Bou Regreg anticline has sedimentary deposits ranging from the Lower Ordovician to the Upper Visean age (*Izart, 1990*). The silicate platform deposits of the Ordovician are overlayed by a thick sedimentary series (200 m) made by microconglomerate, black shales, limestones, sandstone and nodular limestones formations. In some areas, Ordovician deposits are intercalated with pillow lavas and dolerites rocks (*Piqué, 1979; El Hassani, 1990; El Hassani et al., 1991; El Hadi et al., 2014*).

The Sidi Bettache basin located in the south includes deposits derived from erosion and disintegration of the Sehoul block ridges (*Piqué, 1979; El Hassani, 1990; El Hassani et al., 1991; Izart, 1990*) dated from the Famenno-Tournaisian to the upper Visean. They are made by sandstones, limestones and shales formations. Finally, Palaeozoic deposits are roughly overlayed along the Bou Regreg valleys by the Mio-Pliocene to the Quaternary cover (*Piqué, 1979; El Hassani, 1990*).

The PZRT region extends in a rectangular shape with 60 km in length and circa 7 km in width elongated in an E–W direction. Research conducted by *Piqué (1979–1994)* and *El Hassani (1990)* suggested that this zone has known a N–S compressional movement leading to an anticlinal structure elongated E–W with a southward inclination. The core of the anticlinal consists of the Ordovician and Silurian formations, the Famenno-Tournaisian age formations of the Sidi Bettach basin form bands that mark the southern flank of the anticline (*Piqué, 1979*). Others studies (*Cailleux et al.; 1984*) suggested that structurally, this region was affected during the Paleozoic by two dextral strike-slip faults, the first one oriented N80, while the second was oriented about N120.

Lakhloufi et al. (2001) and *Lakhloufi (2002 & 2021)* have achieved many structural researches in this region, their results suggested that the PZRT region corresponds to a mega-shear zone oriented E–W with a minimum displacement of 30 km and was accompanied by two strike-slip faults; a NNW–SSE dextral fault and NE–SW senestral fault which cut perpendicularly the previous structures. This mega-shear event has led to the formation of pre-Palaeozoic and Palaeozoic blocks with lenses shapes. *Lakhloufi (2002 & 2021)* proposed to give this zone the name of "North Mesetian Shear Zone (NMSZ)".

3. Methodology

3.1. Data acquisition

3.1.1. Electrical Resistivity Tomography (ERT)

The object of our survey was to characterize the structural organization of the Palaeozoic formations especially the limestones deposits at the subsurface. The results will help the SDGT company to optimize the operations of extraction of limestone layers. To achieve this goal, electrical tomography method was chosen, it uses inversion techniques to reconstruct a vertical section of true resistivity values for subsurface layers. This geophysical method aims to introduce an electrical current into the soil using current electrodes placed at the surface and measures the drop in current flow potential at potential electrodes. The larger space between the electrodes, the deeper current penetration and more depth determination is possible. This method is based on the capacity of geological layers to resist the flow of electric current, influenced by various factors such as porosity, water content, salinity, and presence of the clay.

The dipole-dipole array was used, it measures values called apparent resistivity which represent a weighted average of the resistivity under the soil according to the geometry between two pairs of electrodes, the current and the measured potential ones. This method offers a way to plot raw data of apparent resistivity values and to get an idea of a cross-section of the subsurface. Inversion software is then used the RES2DINV to convert apparent resistivity values to true resistivity ones in order to create a realistic image of the ground.

The dipole-dipole array has many advantages, it's relatively simple to perform a survey along profile lines, it gives a very detailed image with high resolution and the measures are fast because it offers multichannel capability. Finally, this array helps to cover a wide area and to investigate subsurface structures (*Loke, 2011*).

Data acquisition of ERT was conducted using the ARES II multi-electrode resistivity meter 850 v5.61 (SN: 1603387), the electrode positions were determined using a GARMIN handheld GPS device.

We conducted five electrical profiles with united electrode spacing 5m, however, due to the quality of data, we analysed only four (Fig. 2). Profiles 1 and 2 were established on the west side of the study area having respectively NW–SE direction with 180 m length and E–W direction with length of 120 m. Profiles 4 and 5 were conducted in the south of the study area and 1.5 km far from the SDGT quarry with the same direction NNW–SSE and long respectively 160 m and 120 m.

3.1.2. Vertical Electrical Sounding (VES)

VES method is widely used in geophysical electrical technics to assess the electrical resistivity of subsurface layers. It consists of injecting an electrical

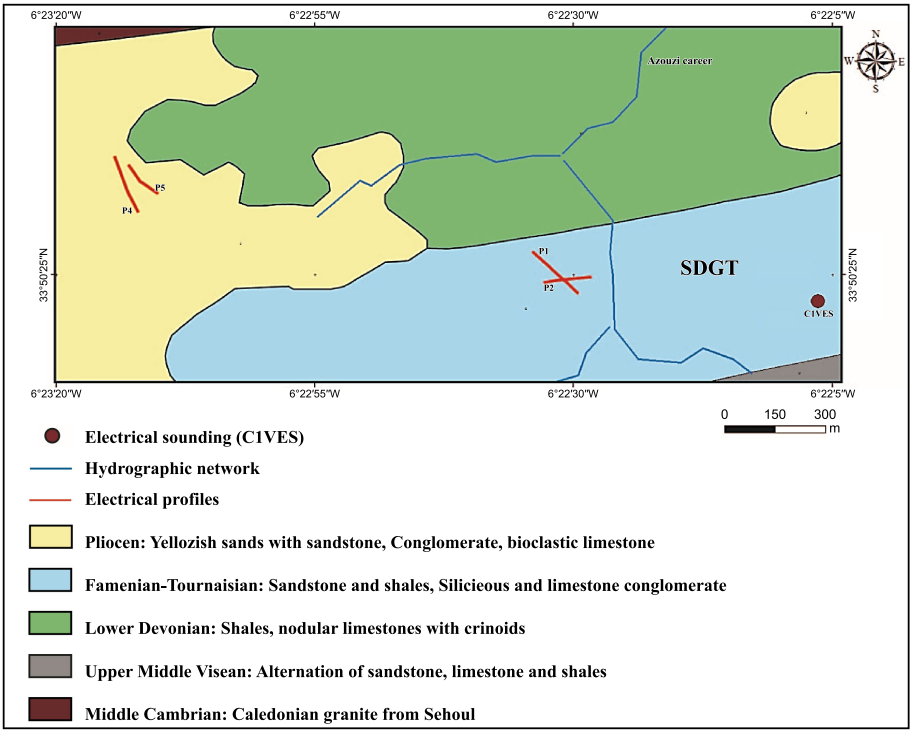

Fig. 2. Location of electrical profiles and geological formations in the study area.

current into the ground through current electrodes labelled A and B, while potential electrodes M and N measure the potential difference. For VES, we used the ARES II 850 v5.61 geophysical equipment (SN: 1603387) with the Schlumberger device. This instrument takes a reading in the mid-point between the current and potential dipoles with progressively increasing spaces. MN electrodes spacing was 2, 5, and 20 m and the AB spacing was adjusted incrementally with 3, 4, 6, 10, 15, 20, and 150 m according to the desired depth of investigation.

A modelling process, IPI2WIN, is then used to generate a 1D resistivity profile as a function of depth. These results are compared with the known resistivity values of the materials to analyse the stratigraphy of the underground layers.

The measured apparent resistivity values were then plotted against electrode spacings (AB/2) to generate a resistivity-depth curve. This curve gives an idea of approximate resistivity ranges for various formations along the subsurface. Trying to correlate layers with limestone deposits is not an easy task because this rock presents a wide range of resistivity values ranging from 50 to 10000 Ωm (*Reynolds, 2011*).

3.2. Data processing

After measurements, inversion software RES2DINV software was used to represent the subsurface in a discrete way using a grid or a series of blocks. The object is to calculate predicted electrical responses and to compare these responses with the observed data (*Loke and Lane, 2004*). This inversion process consists of minimizing the difference between the observed and the calculated data using the least squares method or other mathematical techniques such as the Gauss-Newton method or the Levenberg-Marquardt method (*Loke, 2011*). The least-squares method with smoothing constraint is based on the following equations:

$$\left(\mathbf{J}^{\mathbf{T}}\mathbf{J} + \mu\,\mathbf{F}\right) = \mathbf{J}^{\mathbf{T}}\mathbf{g}\,,$$

$$\mathbf{F} = \mathbf{f_x}\,\mathbf{f_x}^{\mathbf{T}} + \mathbf{f_z}\,\mathbf{f_z}^{\mathbf{T}}\,,$$

where $\mathbf{f_x}$ = horizontal flatness filter,
$\mathbf{f_z}$ = vertical flatness filter,
$\mathbf{J}$ = matrix of partial derivatives,
μ = damping factor,
$\mathbf{g}$ = discrepancy vector.

Finally, with these modelling techniques, we are able to reconstruct the distribution of electrical resistivity true values for the cross section of the subsurface layers.

4. Results, interpretations and discussion

The analysis of 2D electrical resistivity tomography models helps to identify variations in the distribution of electrical properties within the subsurface layers. These variations can include saturation zones, interfaces between different geological formations, or the presence of aquifers (*Gautam and Biswas, 2016*).

Electrical tomography profiles interpretation aims to compare the resistivity values with reference values for various geological materials, for example, limestones show high resistivity values compared to clay or sandstones (*Redhaounia et al., 2016*). This interpretation could be easier and more accurate in case of the existence of boreholes in the study area or with additional data collected during geological surveys.

4.1. Vertical electrical soundings (C1VES)

The analysis of VES profile conducted in the southeastern part of the quarry indicates four different resistivity values interpreted by the existence of four geological formations (Fig. 3). From the surface, a 6 m thick layer with an average resistivity of 60 Ωm, may correspond to deposit mixture of pelite or shale and crushed sandstone. The second one is characterized by a resistivity of approximately 341 Ωm at 6 m depth with a thickness of 9 m. This layer could correspond to limestone rocks and limestone conglomerates. The third layer has low resistivity value circa 7 Ωm and an approximate thickness of 18 m. This layer could correspond to the pelites or argillites due to its high conductivity (*Chouteau and Giroux, 2005*). The deeper fourth layer (more than 33 m) corresponds to the bedrock, characterized by a very high resistivity and could correspond to phyllades and granites formations. These results could be useful while the interpretation of our four 2D electrical resistivity tomography profiles.

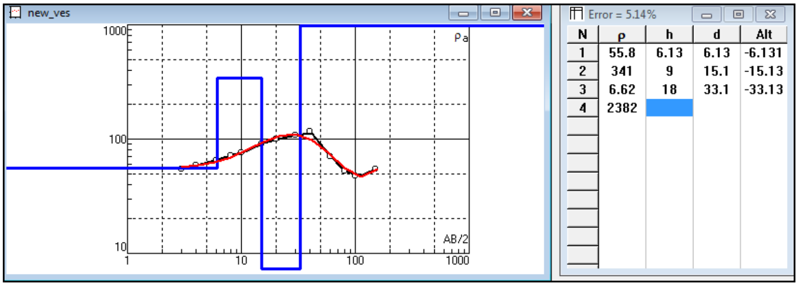

Fig. 3. Vertical electrical sounding results.

4.2. Electrical profile P1 (Fig. 4)

Profile P1 has a NW–SE direction, it shows two units with different resistivity values separated by a discontinuity. The NW unit shows block (1) characterized by low resistivity values ranging from 8 to 67 Ωm, extending from the surface to a depth of 33 meters. This resistivity suggests the presence of pelite and crushed sandstone deposits. On the other hand, the SE unit shows high resistivity values with two distinct geological formations (2 and 3). Layer (2) which is approximately 20 m thick, has resistivity values ranging from about 100 to 800 Ωm, potentially corresponds to fissured limestone blocks, this layer is similar to the entire upper formations of the southern complex at SDGT quarry and has significant potential for the limestone extraction. Layer (3) represents very resistant formations with resistivity exceeding 2000 Ωm, possibly corresponding to magmatic rocks as granites or metamorphic ones as quartzites according to previous geological studies achieved in this region (*Lakhloufi, 2002; Mehdioui et al., 2020; Becker and El Hassani, 2020*). It should be noted that the discontinuity between the two blocks exists from the surface and exceeds 33 m.

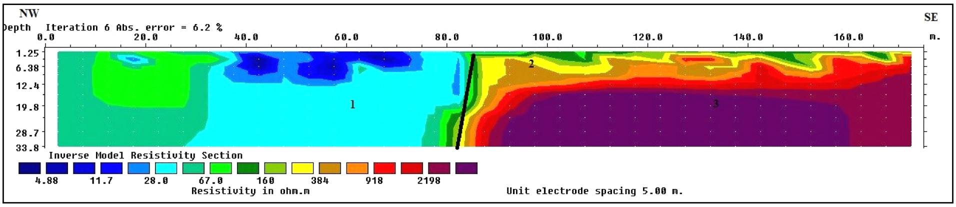

Fig. 4. Inverse model resistivity section of profile 1.

4.3. Profile P2 (Fig. 5)

Profile 2 has an E–W direction, it shows three distinct blocks with different resistivity values. Block (1), situated on the western side of the profile, displays low resistivity values ranging from 3 to 22 Ωm, suggesting the presence of pelite and crushed sandstone deposits. Blocks (2) and (3), located on the eastern side, show moderate resistivity values ranging from 39 to 300 Ωm, likely corresponding to sandstone and limestone formations. Isolate bodies, within block (3) with NW–SE direction and separated by discontinuities, are clearly visible between 60 and 80 m along the profile, indicating results of potential shearing movements that has known this zone in the past.

We note that profile P2 intersects profile P1 on its southeastern side, resistant blocks are observed on the eastern side of profile P2, it's in accordance with the interpretation given in P1. Block (3) in P2 shows resistivity

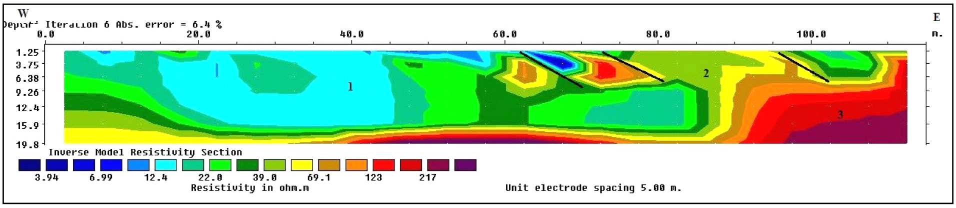

Fig. 5. Inverse model resistivity section of profile 2.

values close to those of the layer located at 6 m with a thickness of 9 m interpreted from vertical electrical sounding (C1VES). These results support the postulate that formations in block (3) of P2 could be limestone or mixture deposits of limestone conglomerate with nodular limestones.

4.4. Profiles P4 (Fig. 6) and P5 (Fig. 7)

Profiles P4 and P5 were located close to each other on the west side of the study area, at a distance of about 1.5 km from the SDGT quarry and have the NNW–SSE direction. P4 shows approximately three distinct resistivity blocks. Block (1) sis in the southeast of the profile displays low resistivity ranging from 3 to 22 Ωm, with a depth exceeding 20 m, it could correspond to pelites and sandstones formations. Block (2) demonstrates moderate resistivity values ranging from 23.4 to 160 Ωm that could be explained by the existence of marl deposits. Block (3) has resistivity values exceeding 160 Ωm, this could correspond to the limestone or limestone conglomerates deposits. In addition, at shallow-depth, we note lenticular bodies (4) with NNW–SSE direction observed along the profile, they have similar range of resistivity values as block (3). These lenticular bodies could correspond to Devonian limestone formations and could be dislocated by a NW–SE dextral strike slip movement that this region has experienced during the hercynian orogeny (post Visean period) as proposed by *Lakhloufi (2002)*. In addition, during our geological survey, many dislocated formations have been observed along the outcrops in diverse places.

Profile 5 displays similar blocks organization to profile 4. We note also the existence of the subsurface lenticular bodies with the same direction and resistivity values as described in profile 4.

To ensure the reliability of the data, different histograms were generated using the RES2DINV software to depict the percentage error of the apparent resistivity (Fig. 8). For profiles 1 and 2, the resistivity measurement error percentage is around 6%. The correlation between the measured and calculated apparent resistivity is nearly perfect, with the data points prop-

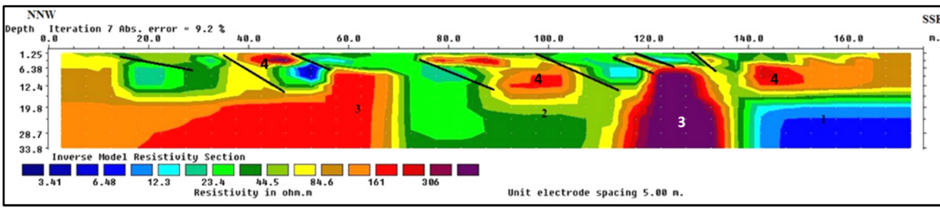

Fig. 6. Inverse model resistivity section of profile 4.

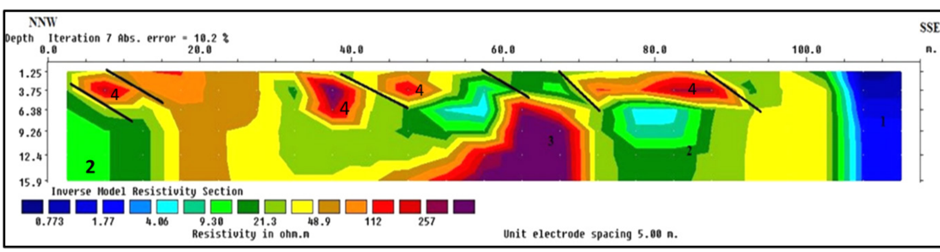

Fig. 7. Inverse model resistivity section of profile 5.

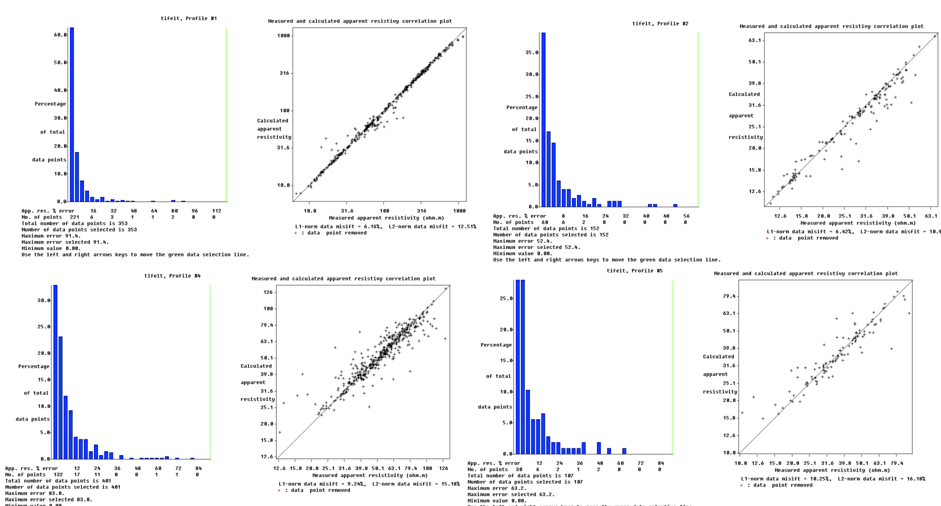

Fig. 8. RMS error for profiles P1, P2, P4, and P5.

erly clustered along the linear curve.

For profile 4, the error percentage is around 9%, and the correlation between the measured and calculated apparent resistivity is quite good. The cloud points follow the curve but it's more concentrated in the middle. Concerning profile 5, the correlation between the measured and the calculated apparent resistivity is not as strong as in the other profiles, but it is still quite good, the error percentage for this profile is around 10%. According to these histograms, we can conclude that the four profiles were well executed.

4.5. Discussion

The analysis of the 2D electrical resistivity tomography profiles 1 and 2, located in the eastern side of our study area and close to the SDGT quarry, help us to have an idea regarding the spatial distribution and depth of Paleozoic formations and specially limestone deposits. Profile 1 shows a southeastern block with high resistivity values which could corresponds to limestone layers suitable for exploitation by the SDGT quarry.

Profiles 4 and 5, located in the west side of our study area and far approximately 2 km from profiles 1 and 2, show lenticular bodies with NNW–SSE direction and different size located at shallow depth.

According to *El Hassani (1994)*, the SDGT quarry, located in the Paleozoic Zone in the Rabat-Tiflet region, belongs to the Aïn El Klab sedimentary series dated Famenno-Tournasian and is formed by sandstones, pelites, siliceous conglomerates, and nodular calcareous conglomerates formations. Also, geological observations show isolated lenticular limestones bodies along the excavated areas in the SDGT and AZOUZI quarries and on the surface (Fig. 9). These structural features indicate the tectonic complexity that have influenced the geologic formations in this particular zone.

Other study carried out by *Lakhloufi (2002)* suggested that the structural organization of the Palaeozoic Zone in the Rabat-Tiflet region has similarities with the Northern Band unit (NB) in the North Mesetian Shear Zone (NMSZ). This zone was described as a wide megashear zone located along the Oued Bou Regreg valley. Various sedimentary rocks ranging from the Cambrian to the Upper Visean, as well as magmatic rocks (Upper Devonian granite and Ordovician basalts), have undergone tectonic dislocation and have led to the formation of tectonic lenses and blocks with different sizes (Fig. 10).

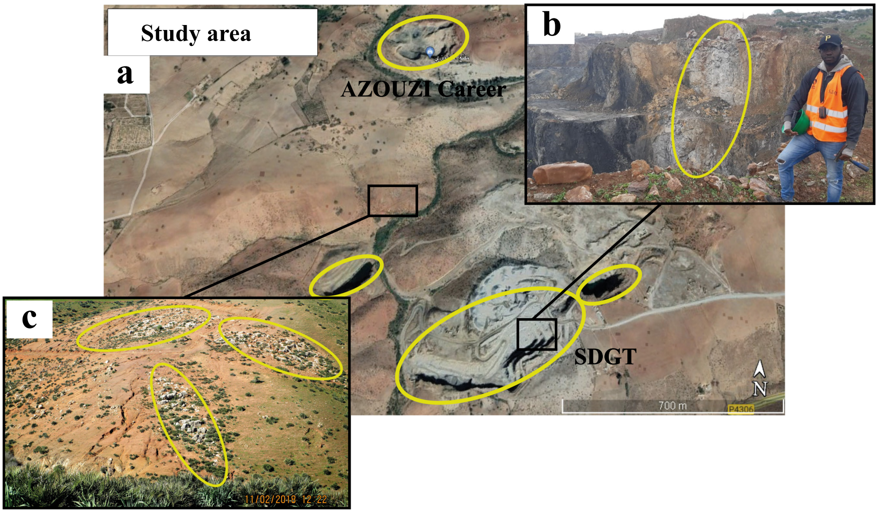

Fig. 9. Lenticular limestone bodies; a) in the SDGT and AZOUZI quarries b) zoom on the SDGT quarry; c) at the surface.

The structural organization described above is well interpreted by section AB with N–S direction (*Lakhloufi, 2002*), it shows lenticular bodies-oriented E–W to NE–SW specially in the North band unit. This interpretation is in concordance with recent satellite image of the study area taken in February 2023 along the Bou Regreg River (Fig. 11).

5. Conclusion

In this study, geophysical investigations, mainly four 2D electrical tomographic profiles and one vertical electrical sounding, were carried out. The analysis of these profiles showed complex structural organization of the Palaeozoic formations in the Rabat-Tiflet region (Morocco) characterized in general by subsurface layers with moderate to high resistivity values that could represent sandstones and limestone conglomerate deposits or isolated lenticular limestone bodies separated by small discontinuities. These lenticular bodies showed a general direction NNW–SSE with a vergence toward the W.

According to previous geological studies leaded by *Lakhloufi et al. (2001)* and *Lakhloufi (2002 & 2021)* in the same region, this structural arrange-

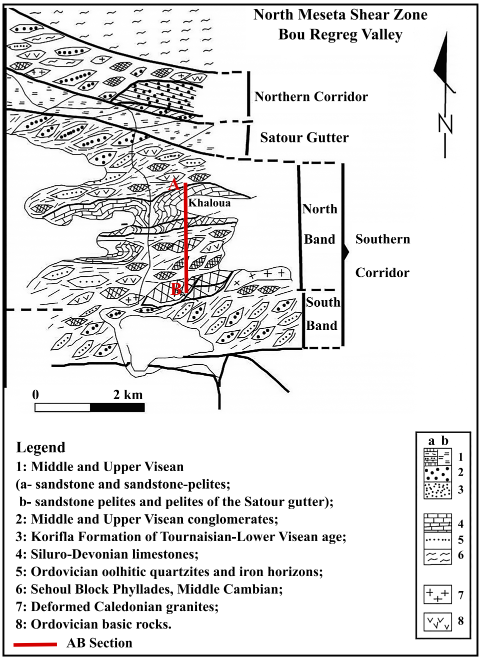

Fig. 10. Different units of the North Mesetian Shear Zone (NMSZ) along the Bou Regreg valley (*Lakhloufi, 2002*).

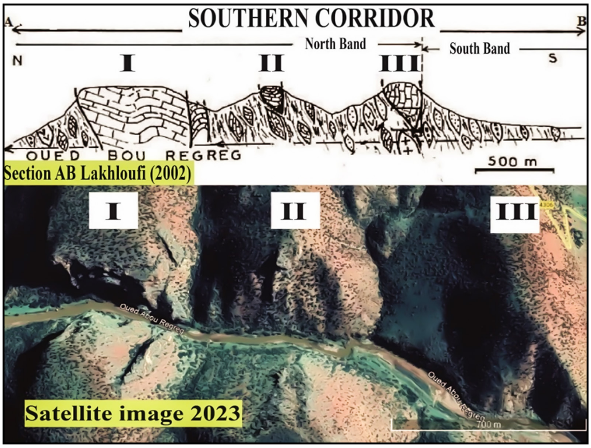

Fig. 11. Section AB of the Southern Corridor along the Bou Regreg valley (*Lakhloufi, 2002*). Notice the similarity between lenticular limestones in the section and the satellite image of the same area taken in February 2023.

ment is in concordance with structures observed in the northern band (NB) of the southern corridor (SC) within what they called the "North Mesetian Shear Zone (NMSZ)". Results of these studies postulate that the NMSZ is made by upper Proterozoic granite, Ordovician basalts and Ordovician to Devonian sedimentary formations. This region has experienced during the Hercynian orogeny (post Visean period) two strike-slip faults; a NNW–SSE dextral fault and a NE–SW senestral fault which gave dislocated and isolated lenses composed by various sedimentary blocks and magmatic rocks. Further, these structural features are in agreement with structures observed in recent satellite images.

The combination of geophysical profiles analysis, geological studies and satellite image observations helps us to contribute to delineate, even in small scale, the structural organization of the Palaeozoic Zone in the Rabat-Tiflet region. These results are valuable for geological mapping, resources assessment and tectonic evolution studies of this region.

To better follow the spatial distribution of limestone formations in the SDGT quarry, part of the Palaeozoic Zone in the Rabat-Tiflet region, more geophysical and geochemical studies are recommended for an effective and sustainable management of these valuable materials.

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