



Contribution of Lasergrammetry, Photogrammetry and Electrical Tomography for the Survey and 3D Representation of Caves: Case Study of the Cave of Kef El Baroud, Province of Benslimane, Morocco

Hicham Benani^{1,*}, Lalla A. Ouzaouit¹, Ayoub Nehili², Larbi Boudad¹

¹ Department of Geology, Mohammed V University, Faculty of Sciences Rabat, Morocco.

² Faculty of Letters and Human Sciences, Sultan Moulay Slimane University, Beni Mellal, Morocco

* Correspondence: hicham.benani@um5r.ac.ma

Abstract

Received:
18 October 2022

Accepted:
21 February 2023

Published:
31 July 2023

The modeling of caves is constantly evolving and the classic modeling tools are giving way to new techniques that are more precise and more practical, indeed scientists are increasingly using 3D modeling to improve the representations of caves, in this study we have used lasergrammetry and photogrammetry which occupy an increasing place in the 3D representation of caves. Their simplicity favors their use for recording and modeling the parietal morphology of caves and the detailed representation of the complexity of Endokarst. As part of the geomorphological study of the Kef El Baroud Cave which is located in the province of Benslimane in Morocco, two modeling methods were carried out, it is a digital survey by lasergrammetry and by photogrammetry of the cave. and its parietal morphologies. The study was completed by a topographical survey with a DistoX rangefinder. The geophysical contribution by electrical tomography was also carried out. The 3D terrestrial laser scanning technique was performed by a LEICA RTC 345 scanner. These measurements made it possible to reconstruct the evolutionary stages of the paragenetic morphologies, and their relationships with the local geomorphology, and the structural elements. The field measurements were integrated into the morphometric analyzes of the digital models, which allowed a large number of observations. The surveys also made it possible to compare the results with those of the photogrammetry carried out by a reflex camera and a wide-angle lens with appropriate editing software. Lasergrammetry and its application have enabled us to precisely position within the point cloud all the details of the covered wall, and thus constitutes, alongside photogrammetry, an interesting means for the geomorphological study of the Caves. An electrical tomography study was coupled with the other measurements and made it possible not only to delimit the walls of the Cave according to the resistivity gradients but also to detect the very probable presence of fractured zones under the Cave which could constitute an aquifer.

Keywords: Karst; Caves; Topography; Lasergrammetry; Photogrammetry; Tomography; Morocco

1. Introduction

Spatial representation is a key element of scientific research. It helps to determine the spatial relationships between geological features and the stratigraphic contexts in which they are found, and to complete the scientific interpretation of a geological object or phenomenon. Although the techniques of

spatial representation of accessible open environments have been well established for a long time, the spatial representation of Caves and Caverns has only been noted since the late 19th century. (Jaillet, 2019). The Cave is a complex environment whose surfaces are not uniform and cannot be seen in their entirety, several attempts have been made to represent a cave, from simple sketches to representations in cavalier perspective, currently 3D modeling has developed considerably with the development of lasergrammetry and photogrammetry..(Maumont, 2010; Delannoy et al., 2001; Jaillet et al., 2011; Sadier, 2013). Indeed, the digital development by lasergrammetry and photogrammetry allowed not only the study of the complexity of the Endokarst which forms the Cave, but also a representation (3D) of reality in virtual mode and in animation mode. (Bu et al., 2017) ; (Felzer and Rinderknecht, 2009) ; (Brown and Lowe, 2005).

The objective of this article is to analyze the various topographical representations of the cave of Kef El Baroud and to show its particularities, its richness and its morphological diversity via several effective and complementary methods. All the topographic representations of the Caves and the karst lead to a distanced image of the Cave, which according to the views is impossible on the ground in a single view, moreover, there are no photographs of a Cave in its entirety given the complexity of the endo-Karstic formations.

2. Location of the Study Area

The Cave is located in limestone massif, in the valley of Oued Cherrat, about 10 km east of the town of Ben Slimane. The opening of the main Cave, is oriented to the east, would measure 25 meters long and 7 meters wide. This site is composed by the connection of two KEF EL BAROUD Caves and an external terrace. The Cave is located in the rural commune of Tizgha, province of Benslimane, Morocco (Fig.1).

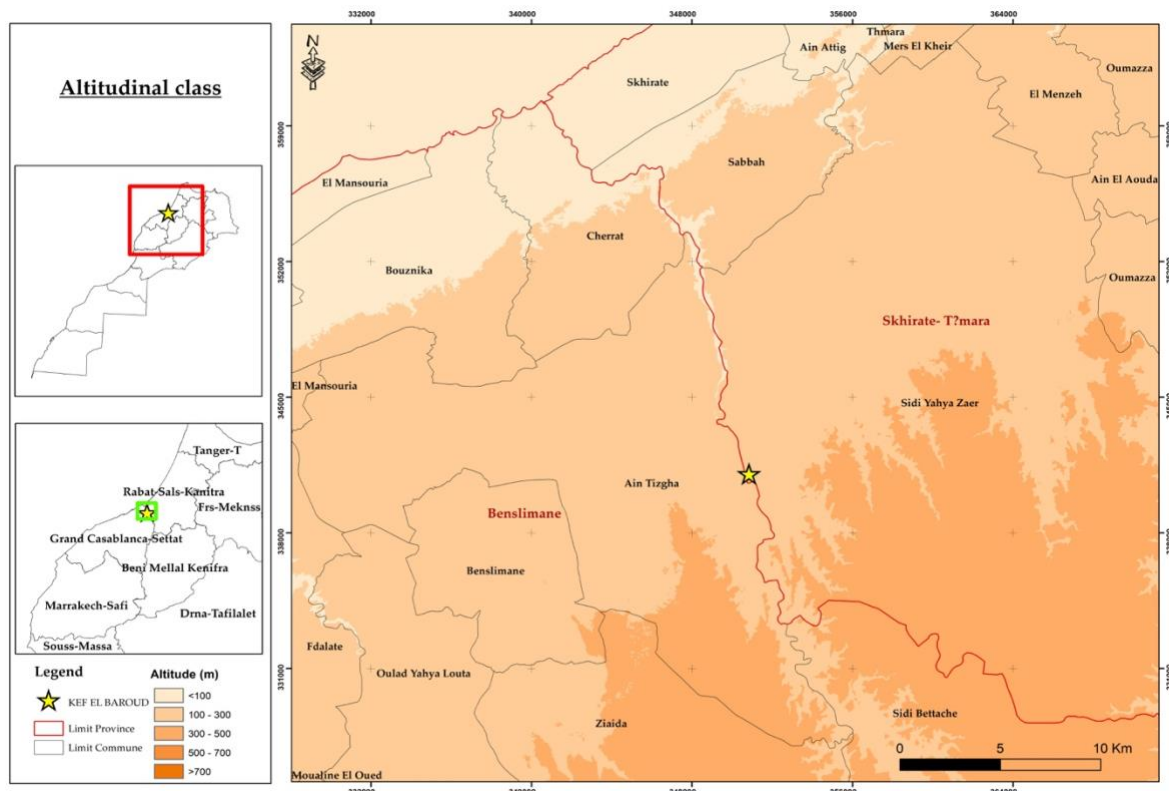


Fig. 1. Location and altitude map of study area.

3. Geological Setting

The study area is located in the Moroccan coastal meseta. The territory, seen from a high point, appears as a plateau of low altitude, sloping to the north and west towards the Atlantic coast and gradually rise to the east and south until reaching an altitude of 500 m. Topographically, the region straddles two major sets: the central plateau and the chaouia. The region of Ben Slimane is part of the Atlasic domain where the ancient lands, folded by the Hercynian orogeny, were levelled and planned, then covered by Cenozoic and Mesozoic Rocks in horizontal layers. We distinguished two different structures in the province:

- The synclorium formation of Rabat located to the east and which is essentially of Carboniferous age, with a dominance of resistant rocks such as quartzites, sandstones and schists.
- The Casablanca anticlinorium formation located in the west of the province and which presents diversified facies belonging essentially to the Cambrian and Ordovician period. They are mainly shale rocks such as the Bouznika shales.

Break through in a reef limestone Massive of Ain Dakhla. Kef El Baroud is composed of two caverns which communicate between them by a very small gallery. (Fig.2).

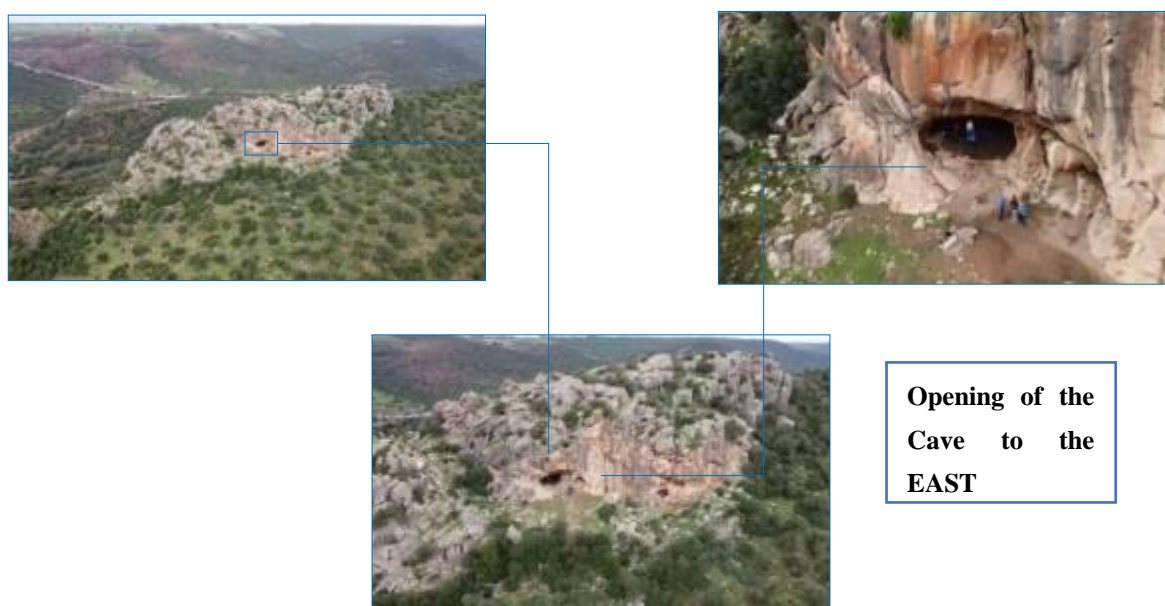


Fig. 2. Location of the Kef El Baroud Cave in the limestone massif of Ain Dakhla

A main room of 26 m long and 7 m wide at the entrance, well-lit and sub horizontal. A steeply sloping Cave that opens onto the top of the massive Cave called the BRETON Cave. (Cornée and Destombes, 1991) (Eichholt and Becker, 2016) (El Hassani and Zahraoui, 1984). The Cave of Kef El Baroud belongs to the succession of the Lower-Middle Devonian of the Western Meseta, it is part of the sub-area of the wadi Cherrat, corresponding to the core of the anticline. The limestones of Kef El Baroud is located near Sokhrat-el Chleuh, of Giletian age. The El Brijat Formation rests directly on these Gavetian limestones, on a significant thickness, estimated by Halouan (1981) at 2000 m, it consists of conglomerate with poorly sorted and angular elements, with a carbonate matrix, attributed to the Lower Famennian. The study area constituted a shallow, warm-climate domain during the Lower and Middle Devonian, marked by a mostly carbonate sedimentation. On this platform Were built reefal bodies. (Cornée and Destombes, 1991; Eichholt and Becker, 2016 ; El Hassani and Zahraoui, 1984) (Fig.3).

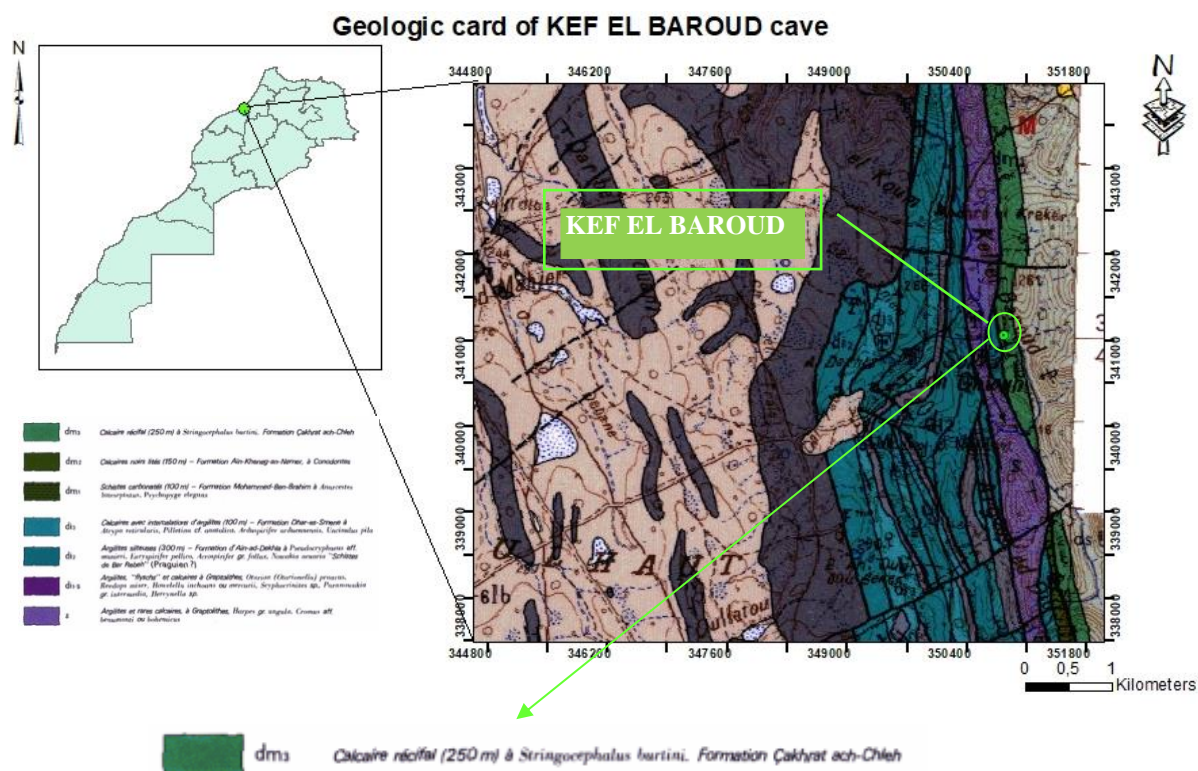


Fig. 3. Geological map of the KEF EL BAROUD study area (Ministry of Energy and Mines 1987).

4. Materials and Methods

The methodology adopted as well as the characteristics of the equipment used for the detailed 3D modeling of the main branch of the Kef El Baroud Cave is well described in Fig. 4. The objective of the use of lasergrammetry coupled with photogrammetry is to concretize a precision 3D and a guided tour of the Cave.

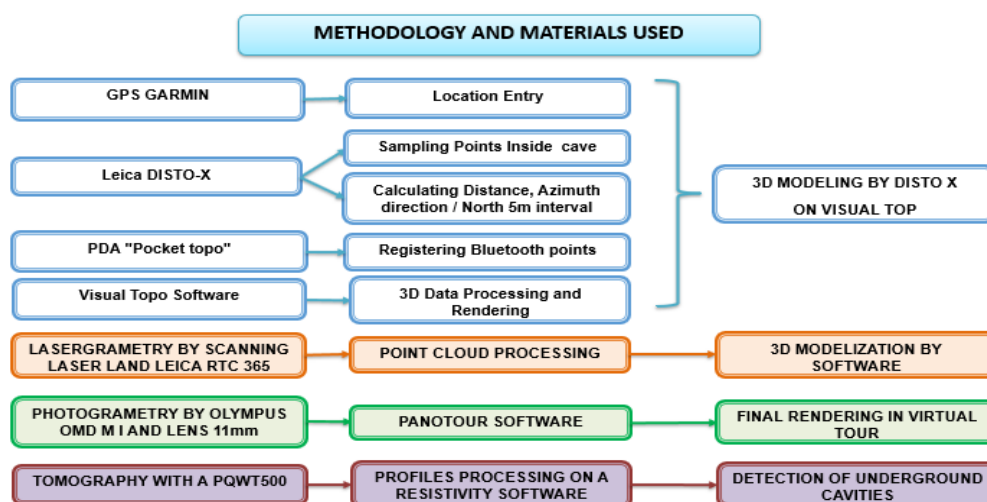


Fig. 4. Methodology of topography by DistoX, photogrammetry, lasergrammetry and tomography of Kef El Baroud

In this study, we used terrestrial laser scanning (TLS) and digital photogrammetry to obtain photorealistic 3D models of the geomorphology of the Kef El Baroud Cave.

Firstly, the conventional topography of the Cave was realized using a technique called "paperless topography" with the use of the DistoX lasermeter and the Personal Digital Assistant, the data were exported to the VISUAL TOPO software for a global rendering of the topography of the Cave. Subsequently, lasergrammetry with the Leica RTC 360 (TLS) scanner was used as a second technique. Finally, the photogrammetry of the Cave was carried out by an Olympus brand camera (OMD) fixed on (Ninja head) and processed by the Panotour software for a remote virtual visit. The final rendering of the 3 techniques, allowed us to have, a faithful graphic information of the Cave and its main structures. The study was completed by electric tomography of the Cave in order to complete the results of the other techniques and to prospect other neighboring cavities not accessible or aquifers zones not listed.

4.1 Topography by Disto-x

The representation of Caves as an extreme and difficult to access environment is made possible and easy with the DistoX. It is a small, compact ($55 \times 31 \times 122$ mm) and light (150 g) instrument, and is the most widely used surveying instrument in the caving community worldwide. Its system is based on a modification of the Leica X310 portable electronic laser rangefinder, a motherboard integrating a module for measuring slope and orientation with respect to north is installed as well as a Bluetooth chip allowing to send data directly to an electronic topography book already installed on PDA or smartphone. (Bussa et al., 1997 ; Reinhart, 2017 ; Cassou and Bigot, 2007 ; Redovniković et al., 2014 ; Azmy et al., 2012). This device was developed to map Cave systems to replace the traditional time-consuming and labor-intensive method of manual measurements and paper sketches (Heeb, 2008) .

4.2. Modeling by Lasergrammetry

The use of lasergrammetry by terrestrial laser scanner is the best way to capture measurements of complex environments, small or large Cave chasms and thus to document in 3D the morphology of Caves. (Benani et al., 2022). Moreover, the Leica laser scanner used is the RTC 360 and is characterized by a measurement rate of up to 2 million points per second and an advanced HDR imaging system, which allowed us to have the reality in 3D with the creation of 3D colored point clouds in less than 2 minutes per station. The data is then processed on a specific software for an accurate and more detailed rendering. (Robert et al., 2014 ; Jaillet et al., 2011 ; Zlot and Bosse, 2014 ; Grussenmeyer et al., 2015 ; González-Aguilera et al., 2009 ; Delannoy et al., 2001).

4.3. Modeling by Photogrammetry

For the photogrammetry several parameters were taken into consideration for the optimal taking of the pictures. Adjustments were made to the resolution, focal length, lens aperture, shutter speed and sensor sensitivity. We photographed 5 stations and in each station we took 26 shots at a rate of 8 photos per angle on 3 different angles in order to have the 360 degree on the one hand and also to have enough areas of intersection between the images for an optimal rendering. (Benani et al. 2023). The 3D modeling by photogrammetry was realized by a reflex camera OLYMPUS OMD MARK I and a wide-angle lens. The 360° panels have been gathered on a specific processing software PANOTOUR to generate a guided virtual tour.

4.4. Electrical Tomography

The principle of the method of electrical tomography or geo-electric used for the study of the Cave (Fig. 5), consists essentially in transmitting, by means of two electrodes, a direct electric current (or low frequency) of known characteristics and to measure the differences of potentials created (d.p.d.).

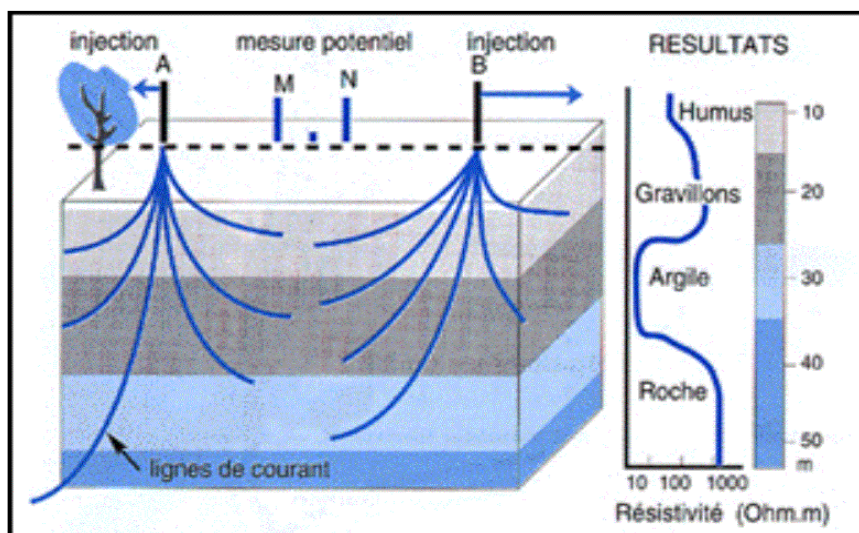


Fig. 5. Principle of the geoelectric method

The need to use four electrodes and not two, is simply explained by the fact that the potential difference that would be measured between the current electrodes would be mainly a function of the resistance of the soil in the vicinity of the electrodes and practically independent of the resistivity of the deeper ground. The basic device, generally composed of four electrodes and a device that allows the transmission of a direct current and the measurement of the resulting p.d.d., offers several variants that can be grouped into two main categories:

- The first one, called "electrical probing", consists in establishing the variation of the resistivity with depth.
- The second one, called "electrical drag", tries to highlight lateral variations of resistivity, adapted to the location of fractured basement zones under cover or level of alteration.

The technique of the vertical electrical survey (VES) allows to study the variation of the resistivity according to the depth. The vertical electrical survey (VES) gives us information on the vertical electrical distribution, at a given point, at the surface.

The electrical drag consists of four moving electrodes whose spacing remains constant and measuring the apparent resistivity as a function of the position of the device (Fig. 6).

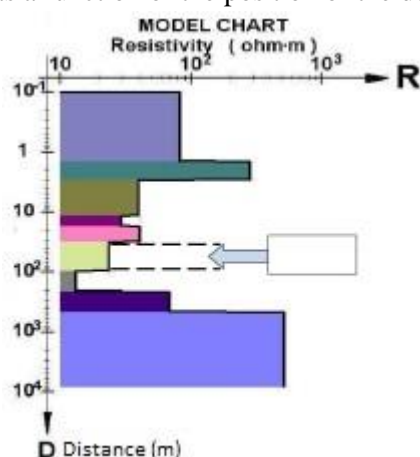


Fig.6. The relationship between the specific resistance and the diffusion area of the electrodes.

As the spacing between the electrodes is fixed, the depth of investigation is relatively constant and the apparent resistivity a measured depends on the lateral variations of the resistivities encountered.

This investigation technique makes it possible to locate faults, karsts, veins, fractures, etc. If the measurements are made along a line, an apparent resistivity profile is established, while if several profiles are made side by side, an apparent resistivity map can be drawn (Fig.7).

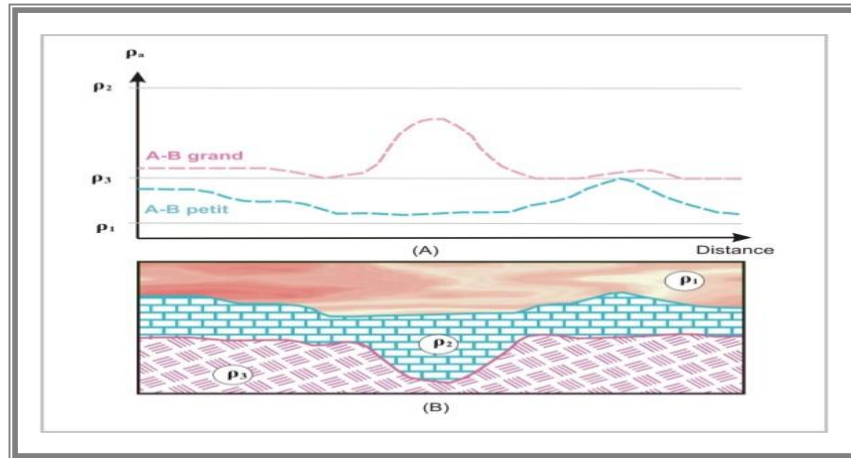


Fig.7. Field implementation of the electric troling technique

The (geophysical prospecting water instruments using the natural electric field as a source of electricity with contrasts in the resistivity of underground rocks PQWT).

series automatic mapping Cave detector is based on the earth's electromagnetic field as the field source, based on the conductivity difference of different underground geological structures, and studying the law of variation of electric field components at different frequencies to study the geological structure and changes, to search for underground geological areas such as underground mines, Caves and tunnels. In this work the surveys were carried out with the Schlumberger array to obtain the lateral changes in resistivities. The spacing between the electrodes being fixed, the depth of investigation is relatively constant. This investigation technique makes it possible to locate, among other things, faults, karsts, veins, fractures, several resistivity profiles have been established.

5. Results

5.1. Modeling by Disto x

In our case the Kef El Baroud Cave was topographed by using the DistoX, this method allows to have information on the orientation, depth and development of the Cave. The result is directly projected on a screen, and allows a wireless transfer of the results to connected device PDA-Trimble Juno "Pocket topo" for an immediate analysis on site of the acquired data. 50 sights carried out for a total development of 120m. The highest point is at +17m, the lowest point at -3m, the positive difference in altitude is +20m. The total volume calculated by the software is 1772 m³.

The sights are completed by a field sketch, including the plan and cross-sectional drawing, with the position of all stations, the notes are taken directly on a Pocket receiver by Blue tough and also taken manually for verification. Then the extension is sent to a software for the drawing of the skeleton and for the 3D dressing. (Fig.8). The software used in the case of the Kef El Baroud Cave is Visual Topo, which gives skeletons in 2D and 3D plan, section and expanded section mode (Buehler, 2009).

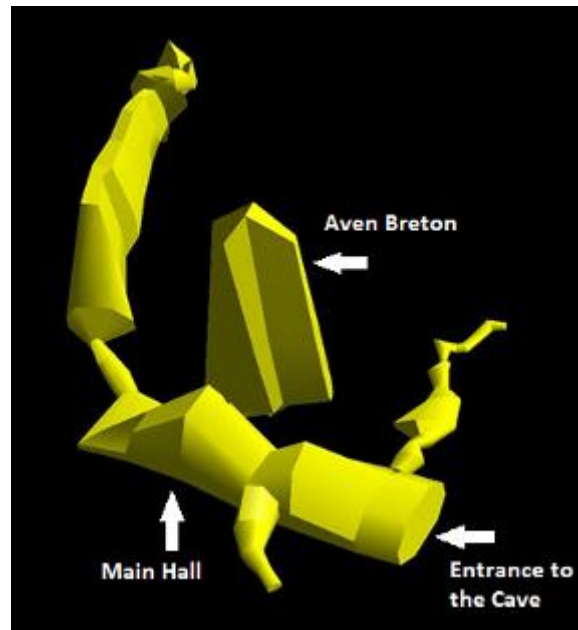


Fig. 8. 3D projection of the KEF EL BAROUD Cave after the walls have been covered by Visual TOPO

5.2. Lasergrammetry by Leica RTC 360

A scan was performed on several stations in order to obtain an efficient and exploitable rendering, in fact with the Leica RTC 360 scanner the fast scan is possible in 360° horizontal and 300° vertical. (Fig.9).

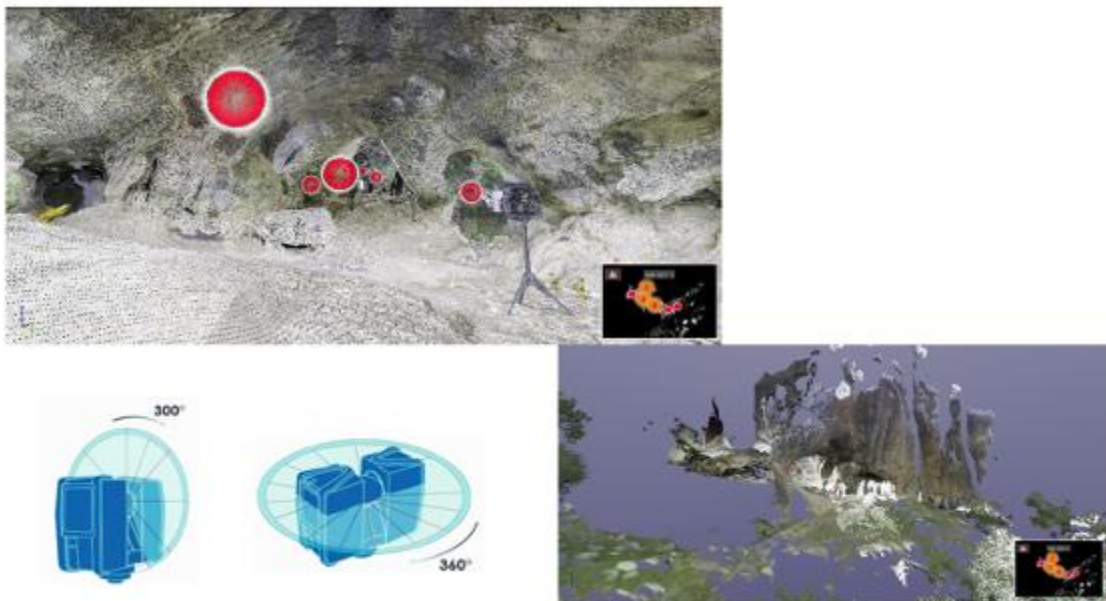


Fig. 9. Horizontal and vertical laser scanning at the KEF EL BAROUD Cave by LEICA RTC 360

A 3D analysis of the underground shapes of the karst is proposed from lasergrammetric surveys, the point clouds obtained by laser scanning were meshed and allowed to produce shapes and calculate the volume of the Cave which amounts to 765713 m³ (Fig.10).



Fig. 10. Lining and Volume of the KEF ELBAROUD Cave

5.3 Photogrammetry of the Cave

Digital photogrammetry allows, from a set of images of the scene to be modeled on different angles and possibly with georeferencing elements for orientation, to have an expression of the results in a reference coordinate system. The rotation system used is a panoramic head Nodal Ninja 3 Mk3, it is a so-called spherical head which allows to photograph on $180 \times 360^\circ$ and thus to carry out complete virtual visits of 360° , it has a plate of adjustment in depth, inclinable on a vertical arm, itself fixed on the low plate. Each plate allows a displacement on 12 cm it is perfect to take the nadir in photo even by long times of pose. The angle chosen between two photos is 45° for each photo in order to cover the 360° required to constitute the 3D model.

The points of interest that represent the same detail on several images are assigned the same identifier and therefore easily located by the image stitching algorithm.

Below the model of image capture adopted by station on three levels in relation to the vertical at 45° , 90° and 135° so as to have a maximum of intersections between the photos necessary for the algorithm to find a maximum of similarity point. (Fig.11).

In total there are 26 photos taken by stations distributed as follows:

- 8 photos taken at 45° of the horizontal axis;
- 8 photos taken at 90° of the horizontal axis;
- 8 photos taken at 135° of the horizontal axis;
- 1 photo on the 0° axis;
- 1 photo on the 180° axis.

We had realized 5 stations thus 5 panoramas totaling 130 photos.

The assembly of the photos was carried out on the software AUTOPANO (Hyvärinen, 2019 ; Wu and Lee, 2017 ;Santos et al., 2018).

Below is the result of the assembly of the five 360° panels on autopano (Fig.12).

STATION 1

	0°	45°	90°	135°	180°	225°	270°	315°	360°
PHOTO SERIES 1 PICS AT 135°		PIC 1	PIC 2	PIC 3	PIC 4	PIC 5	PIC 6	PIC 7	PIC 8
PHOTO SERIES 2 PICS AT 90°		PIC 9	PIC 10	PIC 11	PIC 12	PIC 13	PIC 14	PIC 15	PIC 16
PHOTO SERIES 3 PICS AT 45°		PIC 17	PIC 18	PIC 19	PIC 20	PIC 21	PIC 22	PIC 23	PIC 24
PHOTO SERIES 4 AXIAL PICS	PIC 25				PIC 26				

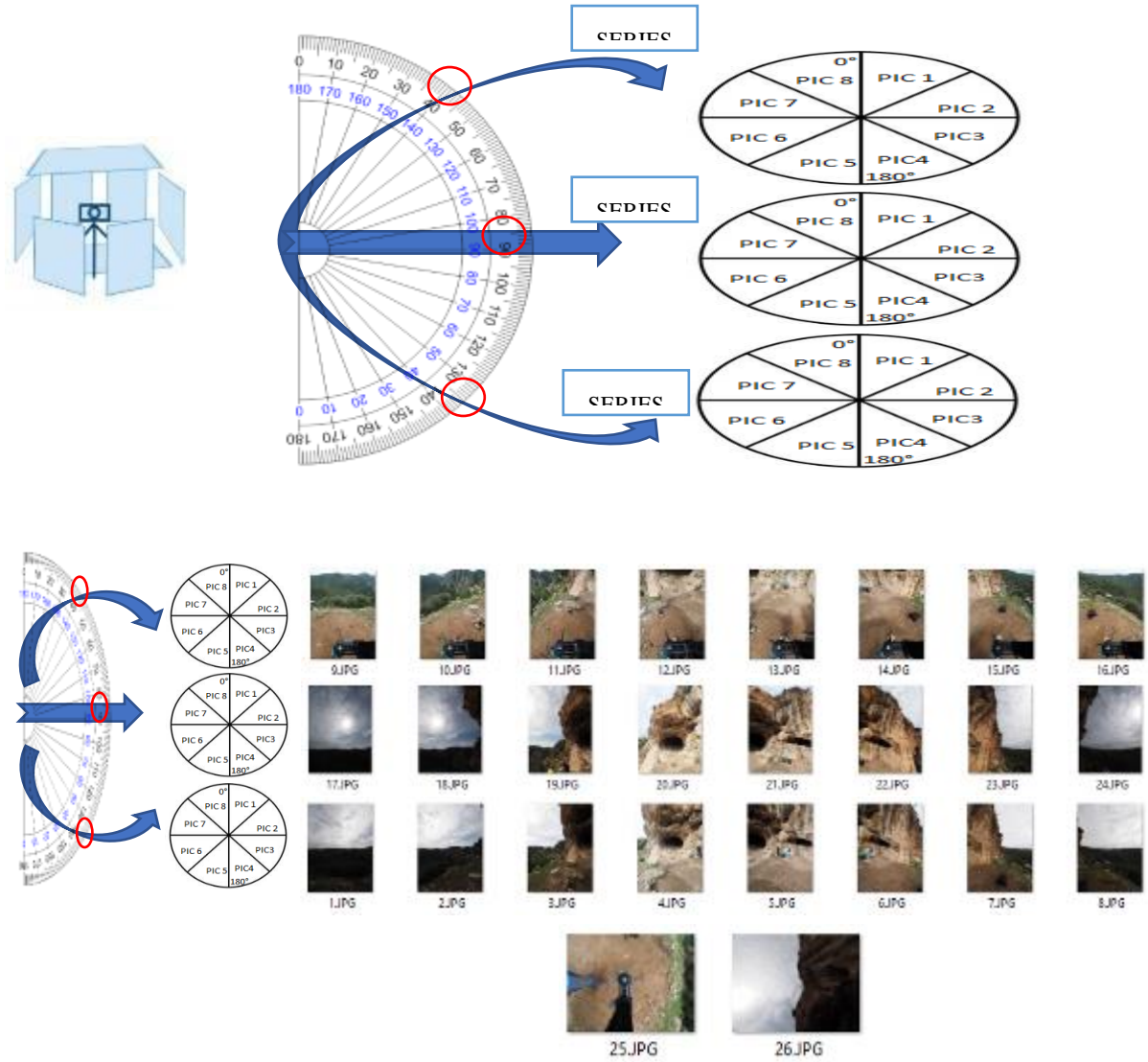


Fig. 11. Summary diagram of the photographic shots by panorama and photos of the station 1 Kef El Baroud Cave

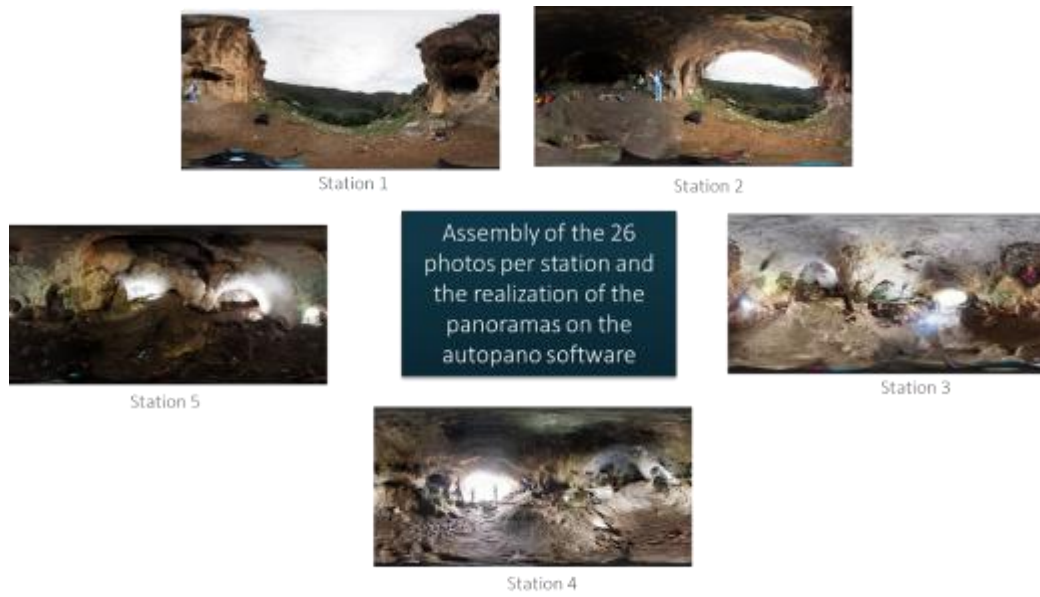


Fig. 12. 360° panel assembly on Autopano

Once the panels are assembled, we proceed to the assembly of the guided tour on the Panotour Giga software. The assembly requires the addition of HOTSPOT to facilitate the navigation. (Fig.13.14).

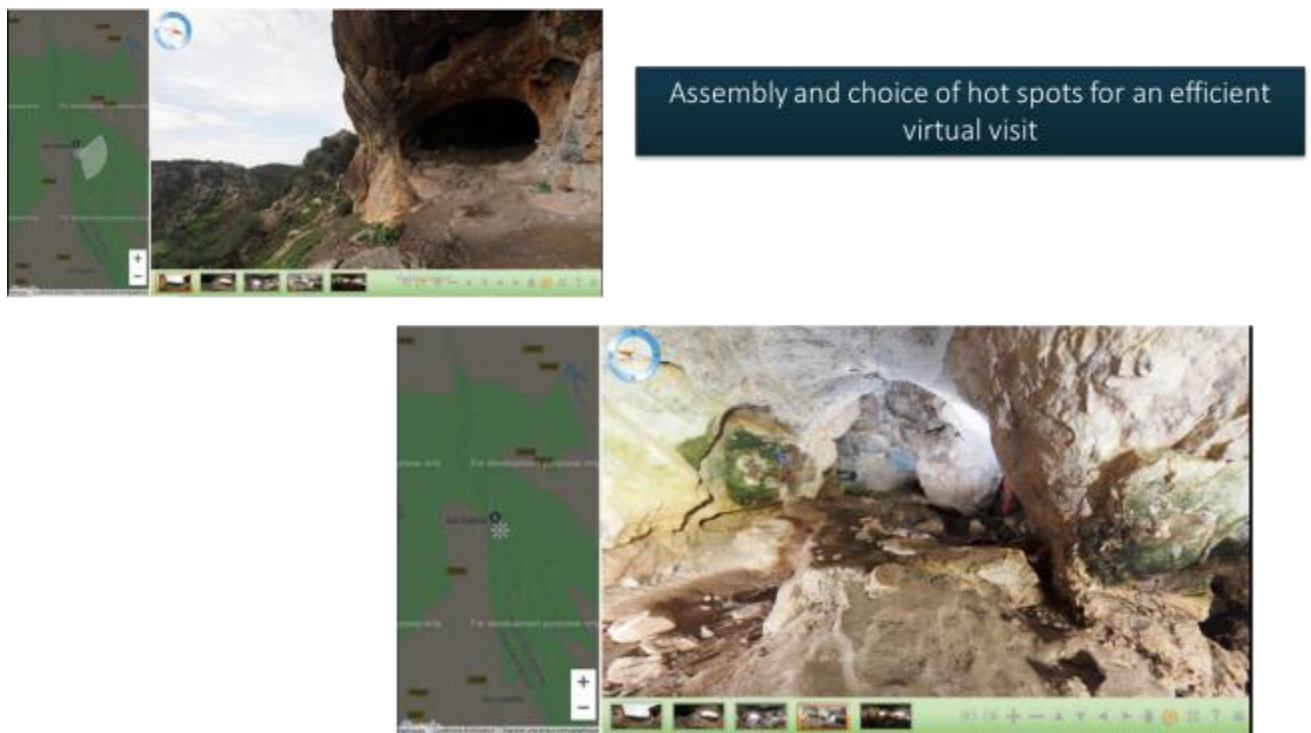


Fig. 13. Visualization of the stations on Panotour and setting up of Hotspots



Fig. 14. Visualization of the stations on Panotour and setting up of hotspots

The Endokarst is a typical example of a geomorphological object that can only be apprehended and studied through its three dimensions (3D). The use of such (3D) analysis is an original and innovative approach to the study of karst networks. Indeed, in the field of Endokarst, the shapes are folded on themselves and superimposed, resulting in a geometric information that the classical representations (raster type) do not allow to represent them correctly. For example, by taking the "right" pictures, it is now possible to realize in a few hours a panorama and a guided tour of the Endokarst.

5.4. Tomography of the Cave

The geoelectrical method allows a global recognition of the studied sector by determining the physical parameters (resistivities) and geometric parameters (thickness) of the subsoil. Significant developments have been made and now provide fast multi-electrode acquisition devices, optimized measurement protocols, and (2D and 3D) inversion codes (Penz, 2012) (Chalikakis, 2006). In addition to the simplicity of its implementation in the field, it allows a recognition of the investigated site and gives a quantitative image of the resistivities and thicknesses of the different layers of the ground.

In the case of the Kef El Baroud Cave, we proceeded to the installation of 5 electrical profiles (Fig. 15) for the measurement of the resistivity of the rocks in order to predict the continuity of the cavities or even the detection of other cavities not yet explored or inaccessible.

Five profiles were laid with a continuous electric current and a DDP potential difference receiver to record the signals, see below the results of the resistivity maps and resulting models.

PROFILE 1

Scale: one scale=5m depth

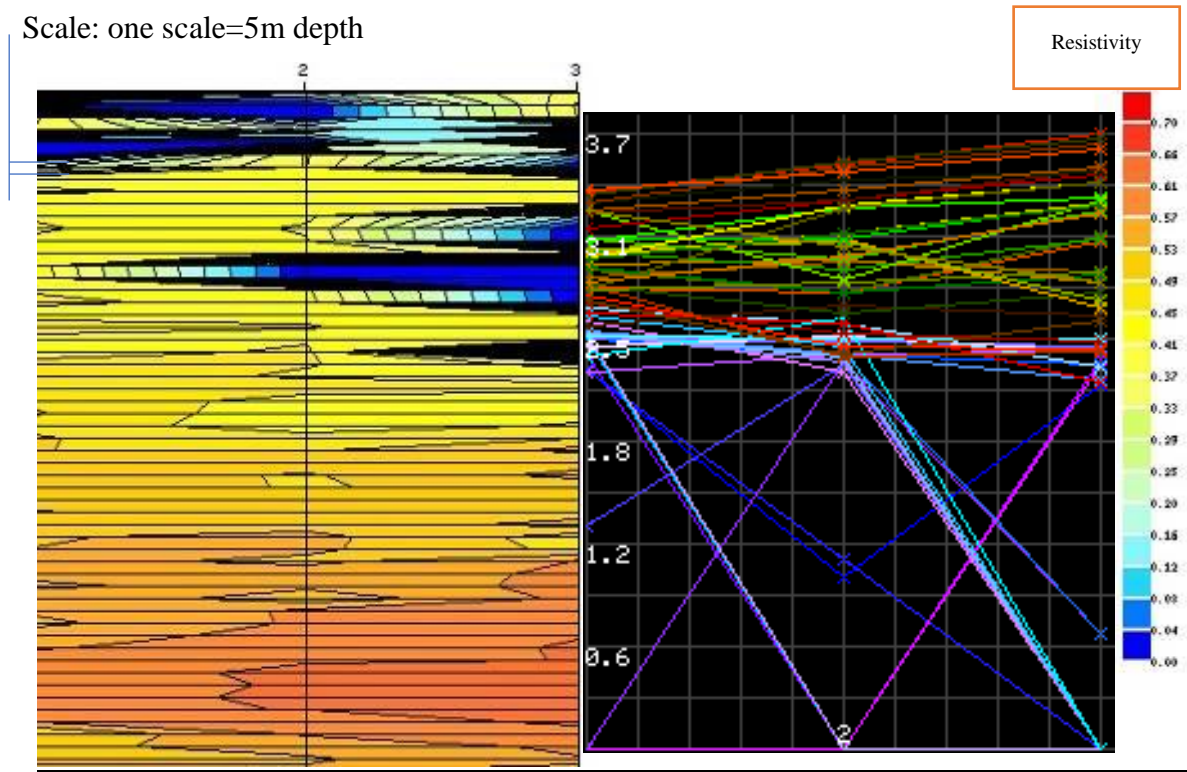


Fig.15. Resistivity map of profile 1: diagonal section through the Cave

PROFILE 2

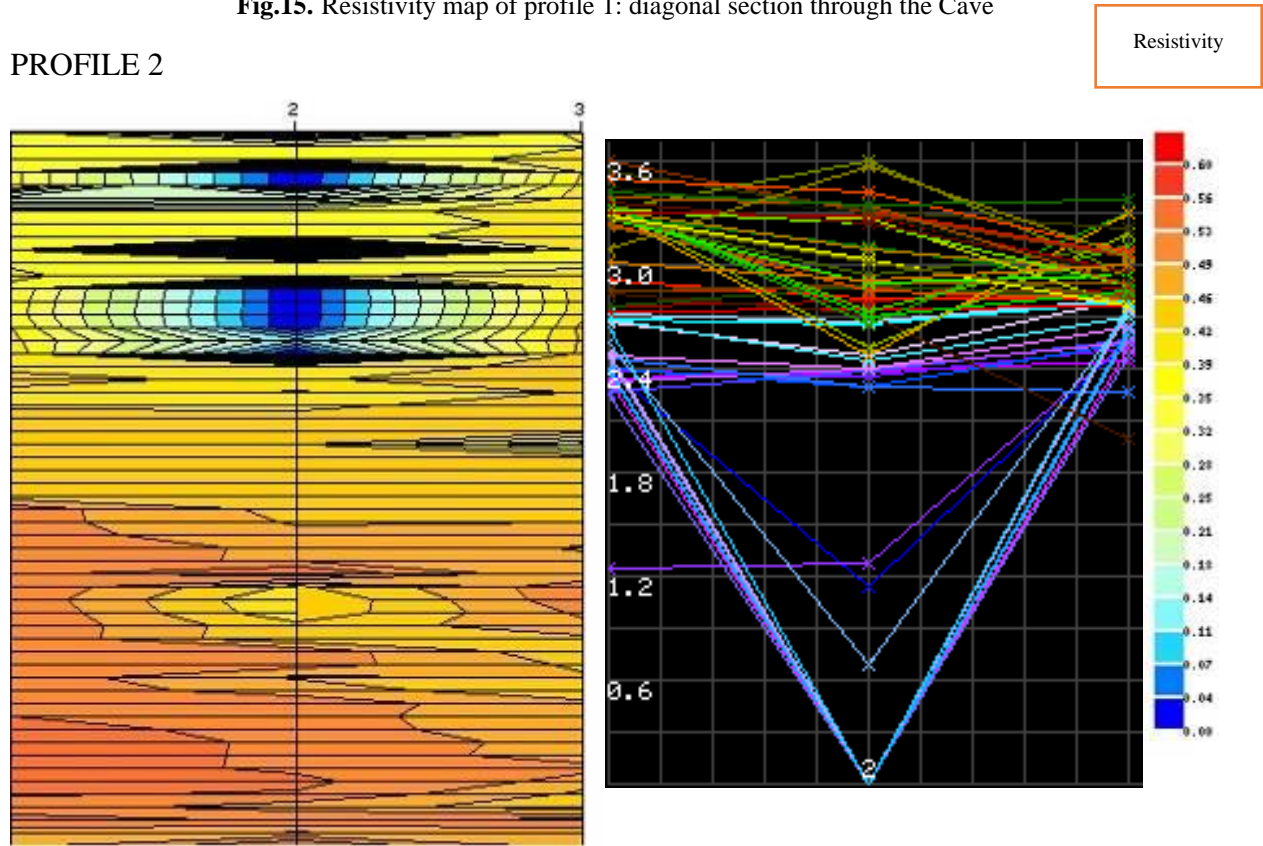


Fig.16. Resistivity map of profile 2: the cross section of the Cave

PROFILE 3

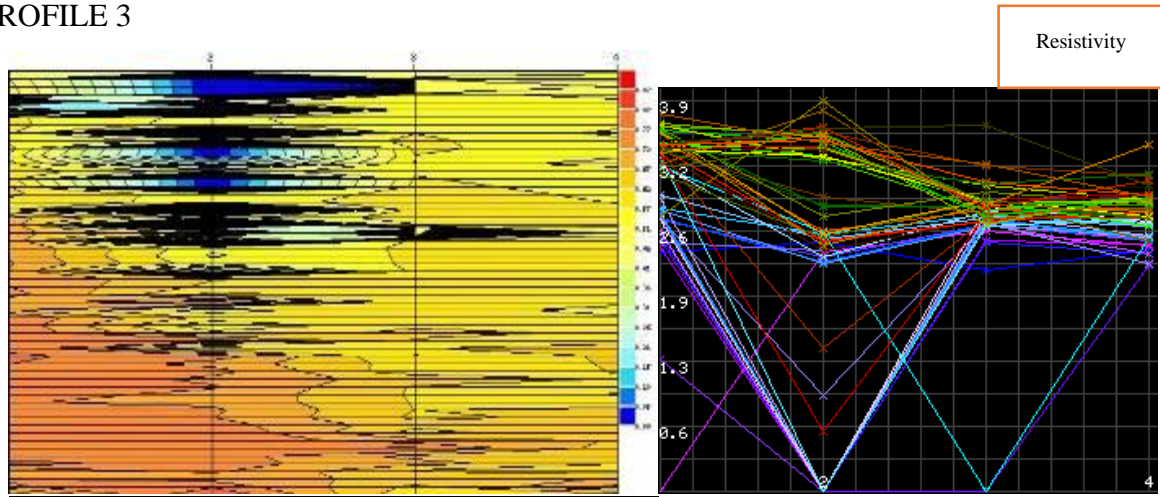


Fig.17. Resistivity map of PROFILE 3, semi diagonal section through the Cave

PROFIL 4

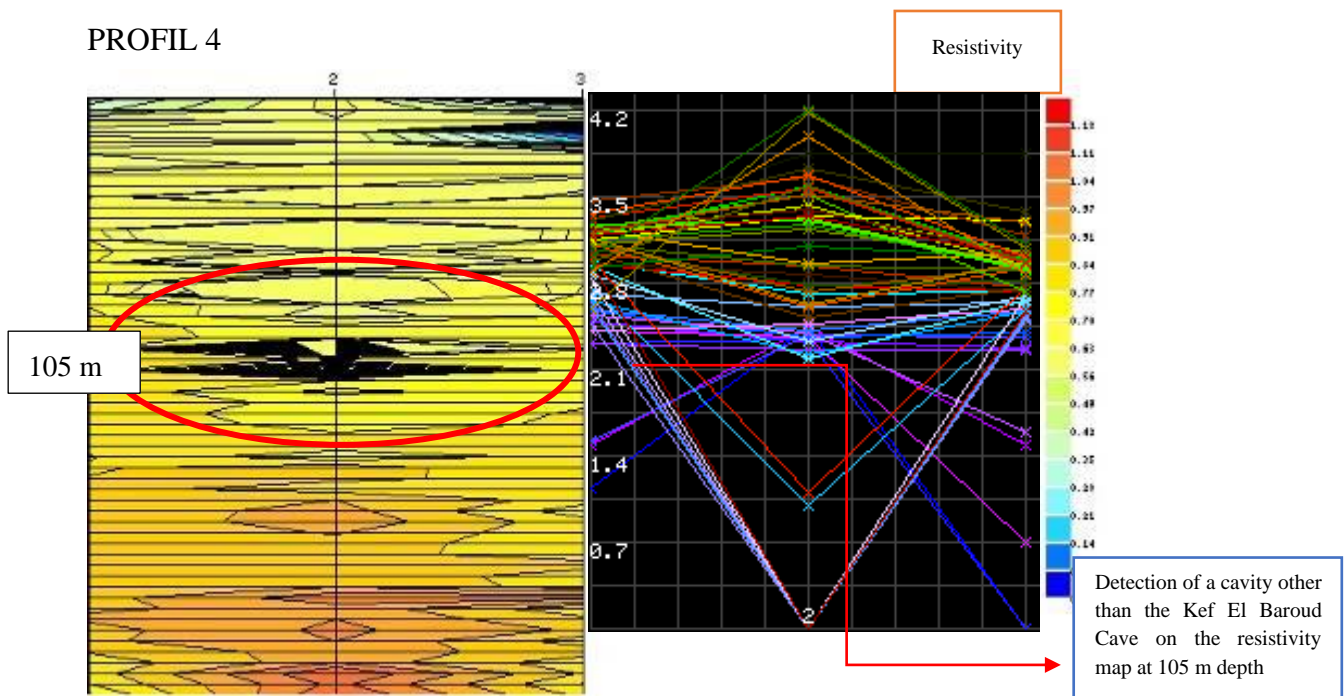


Fig.18. Resistivity map of PROFILE 4, lateral section including the end of the Cave

PROFILE 5

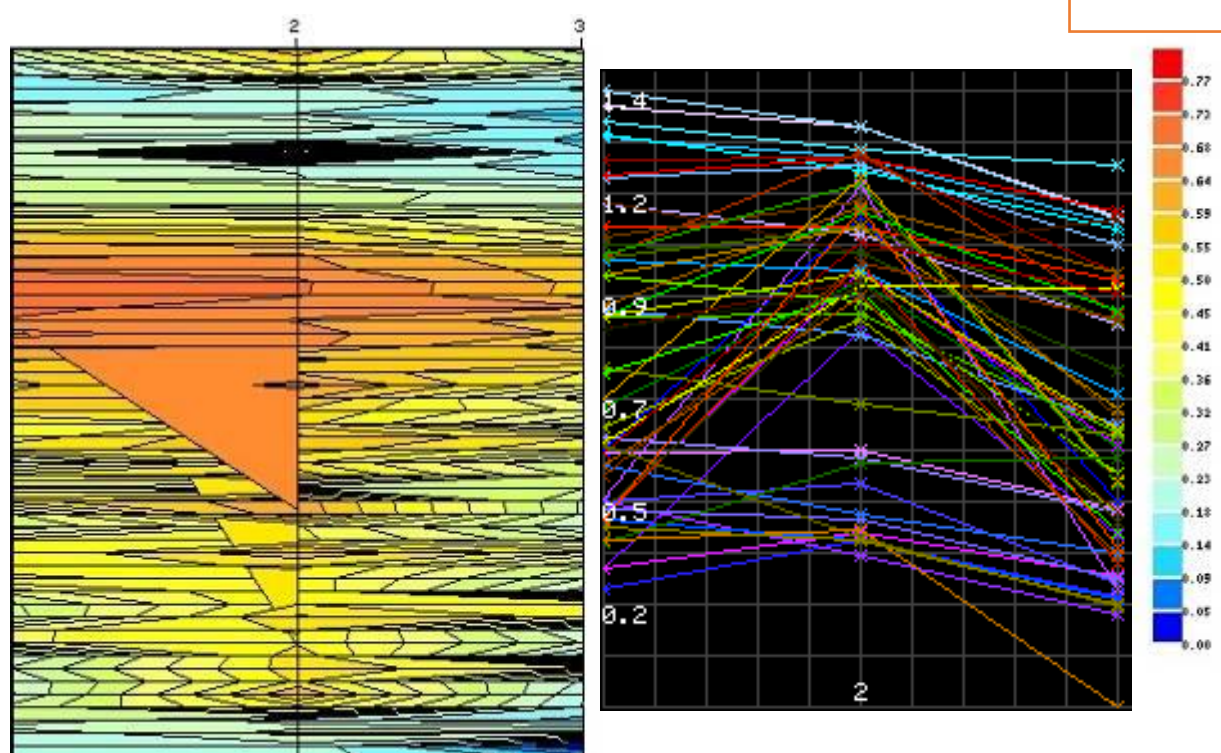


Fig.19. Resistivity map of PROFILE 5, longitudinal section inside the Cave

The profiles 1,2, and 3 (Fig.15,16,17), all show a total fall of the resistivity to the value 0 on the resistivity curve with the detection of the cavity corresponding to the Cave EL BAROUD on the resistivity map and also the detection of a zone of very low resistivity below the Cave. We notice on the other hand in the fourth profile which represents the lateral section including the end of the Cave (Fig.18), Disappearance of the fractured zone below the Cave. The longitudinal section carried out inside the Cave, profile 5 (Fig.19), shows a partial fall of the resistivity on the curve and the detection of fractured zone below the Cave likely to constitute an aquifer on the resistivity map. These results show the interest of electrical tomography in the detection and delimitation of underground cavities.

The combination of the results of the data from the different electrical profiles made it possible not only to delimit the low resistivity and high conductivity zones but also to detect the very probable presence of fractured zones under the Grotto likely to constitute an aquifer.

6. Discussion

The immediate advantages of lasergrammetry are the speed of acquisition, the reliability and the high accuracy of the results. Moreover, lasergrammetry works on homogeneous surfaces, and on almost all materials; the acquisition can also be done at night. Photogrammetry, on the other hand, requires well textured and adequately illuminated materials.

However, lasergrammetry has some disadvantages compared to photogrammetry:

High equipment cost: the average lasergrammetry equipment is more expensive than the average photogrammetry equipment (Deseilligny and Cléry, 2011). Admittedly, there are small triangulation scanners at very low cost (Starterkitet 2014), but their shallow depth of field makes them quite tricky to use one notes; The average weight of the laser scanner often greater than that of the camera, the laser technology more complex to handle, and which requires ad-hoc training (Boehler and Marbs 2004) and finally the difficulty of performing laser acquisition on unstable ground (Heno et al. 2014).

On the other hand, the simplicity of implementing photogrammetry makes it usable in a variety of conditions: cluttered area, little setback, inability to use a heavy tripod ; Photogrammetry is able to produce textured 3D models while the laser requires additional images to obtain the texture.

However, it must be recognized that photogrammetry also has limitations: it fails, for example, to treat shiny or too uniform objects. The qualification of data produced by photogrammetry is also more delicate than in lasergrammetry).The combined use of lasergrammetry, photogrammetry and topography of the Kef El Baroud Cave has helped us to understand the geomorphology of the Cave.

If the techniques used complement each other, photogrammetry has become today a very competitive means of 3D modeling for the modeling of Caves, indeed it gives results comparable to those of laser scanners for a much lighter and less expensive equipment.The final rendering of the treatment shows the interest of the 3D modeling in the exploitation of the Cave of Kef El Baroud which will be a typical example of the exploitation of this heritage by developing an interactive visualization in the virtual space of the Cave. The recording of spatial data with a 3D digital restitution of The KEF EL BAROUD Cave allowed to evaluate the volumetry of the Kef El Baroud Cave and to visualize in a virtual way its complexity. The electrical tomography brings an interest in the delimitation of the Caves but also in the detection and the prediction of the non accessible cavities.

The models developed from the profiles have proven to be extremely informative in imaging the karst environment of the Kef El Baroud Cave. The morphological limits are identified in the east and west of the site by studying the variability of the resistance and the identified conductive anomalies. Moreover this method was not conclusive for the 3D modeling of the Kef El Baroud Cave indeed the geographical situation of the Cave and the limit of the profiles used were not sufficient to deduce a 3D model, on the other hand the geophysical method showed a major interest to reveal the inaccessible cavities and the water-bearing zones and of underground flow not perceptible.

6. Conclusions

The objective of this article was to analyze the different topographical representations of the Kef El Baroud cave and to show its particularities, its richness and its morphological diversity via several effective and complementary methods. All the topographic representations of the Caves and the karst lead to a distanced image of the Cave, which according to the views is impossible on the ground in a single view, moreover, there are no photographs of a cave in its entirety.The studies applied strictly to the geomorphology of the Endokarst are still to be developed because the information extracted from the 3D models resulting from the lasergrammetric surveys is precisely information of the morphological type.However, the use of lasergrammetry remains limited due to the still high acquisition costs and more complex and inaccessible computer processing. The aim was to explore the potential of 3D modeling in an underground environment, taking into account geomorphological issues and problems. The examples presented here undoubtedly show the wealth of information that can be extracted and analyzed, but also the complexity of 3D, both in the survey and in the resulting processing.

Geophysical models of resistivity are known to bring several advantages in the detection of voids or imperceptible and inaccessible aquifers, the study applied to the Kef El Baroud cave has clearly shown the existence of a deep void, others exploration will be necessary to confirm the presence or absence of water.

Acknowledgements

This work was carried out as part of the research conducted on the Cave Kef El Baroud, several people have participated in the work of acquiring data on the ground, we would like to thank all Cavers who have contributed to this work in particular the members of the Association Moroccan Explorers and the Association Randoxygène.

References

- Azmy, S.N., Sah, S.A.M., Shafie, N.J., Ariffin, A., Majid, Z., Ismail, M.N.A. and Shamsir, M.S., 2012. Counting in the dark: Non-intrusive laser scanning for population counting and identifying roosting bats. *Scientific Reports*, 2(1), 524.
- Benani, H., Ouzzaouit, L.M., Boudad, L., Rhinane, H., Nehili, A., El Khalki, Y. and Slimani, N., 2022. Topographic survey with disto x and 3D representation of the caves by laser grammetry, case of the AZIZA cave, Errachidia, Morocco. *The Iraqi Geological Journal*, 21-34.
- Benani, H. et al. (2023) 'Discovery of the teleosauroid crocodylomorph from the early Jurassic of Chaara cave, Middle Atlas of Morocco', *Journal of African Earth Sciences* 198, 104804. <https://doi.org/10.1016/j.jafrearsci.2022.104804>.
- Benani, H., Nehili, A., Ouzzaouit, L.A., Jouve, S., Boudad, L., Masrour, M., Jalil, N. and Arrad, T.Y., 2023. Discovery of the teleosauroid crocodylomorph from the early Jurassic of Chaara cave, Middle Atlas of Morocco. *Journal of African Earth Sciences*, 198, 104804.
- Bu, Y., Xie, L., Liu, J., He, B., Gong, Y. and Lu, S., 2017. 3-Dimensional reconstruction on tagged packages via RFID systems. In 2017 14th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON), 1-9, IEEE.
- Buehler, Y., 2009. Mapping urban and peri-urban agriculture using high spatial resolution satellite data', *Journal of Applied Remote Sensing*, 3(1), 033523.
- Bussa, M.P., Fava, L., Ferrero, L., Grasso, A., Ivanov, V.V., Kisel, I.V., Konotopskaya, E.V. and Pontecorvo, G.B., 1997. Application of a cellular automaton for recognition of straight tracks in the spectrometer DISTO. *Computers & Mathematics with Applications*, 34(7-8), 695-701.
- Cassou, J.P., And Bigot, J.Y., 2007. Le Labyrinthe De La Grotte De Sakany (Quié, Ariège)', 8.
- Chalikakis, K., 2006. Application de méthodes géophysiques pour la reconnaissance et la protection de ressources en eau dans les milieux karstiques. phdthesis. Université Pierre et Marie Curie - Paris VI.
- Cornée, J.J., and Destombes, J., 1991. 'L'ordovicien de la partie W du massif ancien du Haut-Atlas occidental (Maroc hercynien)', *Geobios*, 24(4), 403-415.
- Delannoy, J.J., Debard, E., Ferrier, C., Kervazo, B. and Perrette, Y., 2001. La cartographie morphologique souterraine: apports aux reconstitutions paléogéographiques et paléoenvironnementales. Application à la grotte Chauvet (Ardèche-France)/Subterranean géomorphologie cartography: interest for paleogeographic and paleoenvironmental reconstitutions: application to the "Grotte Chauvet"(Ardèche-France). *Quaternaire*, 12(4), 235-248.
- Eichholt, S. and Becker, R.T., 2016. Middle Devonian reef facies and development in the Oued Cherrat Zone and adjacent regions (Moroccan Meseta), *Facies*, 62(2), 7.
- El Hassani, A. and Zahraoui, M., 1984. Structure des Terrains Paleozoiques au Sud-Est de Rabat Meseta Cetiére Maroc, Maroc. *Trav. Inst. Sci., Sér. Géol et Géog. Phys.*, 16.
- Felzer, T. and Rinderknecht, S., 2009. 3DScan: an environment control system supporting persons with severe motor impairments', in *Proceedings of the 11th international ACM SIGACCESS conference on Computers and accessibility*. New York, NY, USA: Association for Computing Machinery (Assets '09), 213-214.
- González-Aguilera, D., Muñoz-Nieto, A., Gómez-Lahoz, J., Herrero-Pascual, J. and Gutierrez-Alonso, G., 2009. 3D digital surveying and modelling of cave geometry: Application to paleolithic rock art. *Sensors*, 9(02), 1108-1127.
- Grussenmeyer, P., Burens, A., Guillemin, S., Alby, E., Allegrini Simonetti, F. and Marchetti, M.L., 2015. 3D recording methodology applied to the grotta scritta prehistoric rock-shelter in Olmeta-Di-Capocorso (Corsica, France). *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40, 179-185.
- Heeb, B., 2008. A General Calibration Algorithm for 3-Axis Compass/Clinometer Devices, 16.
- Hyvärinen, A., 2019. 360-teknologian hyödyntäminen virtuaalikampuksen toteuttamisessa.
- Jaillet, S., Sadier, B., Hajri, S., Ployon, E. and Delannoy, J.J., 2011. Une analyse 3D de l'endokarst: applications lasergrammétiques sur l'aven d'Orgnac (Ardèche, France). *Géomorphologie: relief, processus, environnement*, 17(4), 379-394.
- Jaillet, S., 2019. L'image topographique du karst et des grottes : représentations 2D et technologies 3D, entre réalité et imaginaire'. *Géomorphologie : relief, processus, environnement* 25, 191-205.

- Maumont, M., 2010. L'espace 3D : de la photogrammétrie à la lasergrammétrie', In Situ. Revue des patrimoines, (13).
- Penz, S., 2012. Modélisation et inversion de données électriques en courant continu : vers une prise en compte efficace de la topographie. phdthesis. Ecole Nationale Supérieure des Mines de Paris.
- Redovniković, L., Ivković, M., Cetl, V. and Sambunjak, I., 2014. Testing DistoX device for measuring in the unfavourable conditions. Proceedings of INGEO, 3-4.
- Reinhart, H., 2017. Contextualizing Cave Maps as Geospatial Information: Case Study of Indonesia, IOP Conference Series: Earth and Environmental Science, 98, 012031.
- Robert, E., Egels, Y., Vigears, D., Schelstraete, D., Pierrot-Deseilligny, M., Boche, E. and Vialou, D., 2014. L'apport des modélisations 3D pour l'étude de la grotte Blanchard (Saint-Marcel, Indre, France), bilan et perspectives pour l'analyse croisée des données. PALEO: Revue d'Archéologie Préhistorique,(spécial), 135.
- Sadier, B., 2013. 3D et géomorphologie karstique : La grotte Chauvet et les cavités des Gorges de l'Ardèche. phdthesis. Université de Grenoble.
- Santos, I., Henriques, R., Mariano, G. and Pereira, D.I., 2018. Methodologies to represent and promote the geoheritage using unmanned aerial vehicles, multimedia technologies, and augmented reality. Geoheritage, 10, 143-155.
- Wu, S.T., and Lee, B.W., 2017. An Innovative Way of Guided Tour: A Virtual Experience of Dark Tourism', in 2017 International Conference on Information, Communication and Engineering (ICICE). 2017 International Conference on Information, Communication and Engineering (ICICE), 208–210.
- Zlot, R. and Bosse, M., 2014. Three-Dimensional Mobile Mapping of Caves, Journal of Cave and Karst Studies, 76, 191–206.