TOMOGRAPHIE (OUTIL GÉOPHYSIQUE) AU SERVICE DE L'ARCHÉOLOGIE: EXEMPLES DE STRUCTURES D'HABITATS AU MAROC ORIENTAL

BY

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ABSTRACT

[EN] TOMOGRAPHY (GEOPHYSICAL TOOL) SERVING ARCHAEOLOGY: EXAMPLES OF HABITAT STRUCTURES IN EASTERN MOROCCO: Electrical Resistivity Tomography (ERT) represents a non-invasive geophysical approach essential for archaeological prospection before and during excavations. It allows archaeologists to investigate subsurface structures, delineate areas of interest, and reduce destructive digging by providing high-resolution images of buried features. This study demonstrates the effectiveness of ERT in detecting subsurface archaeological structures at two significant sites in Eastern Morocco: Guenfouda Cave (Province of Jerada) and Reggada-Jrawa (Province of Berkane). Using a Syscal Pro system with 24 active electrodes in dipole–dipole configuration, five resistivity profiles were conducted with varying electrode spacings (0.5 m, 1 m, 2 m and 5 m) to achieve different penetration depths ranging from approximately 2 m to 25 m. The data were processed using Res2Dinv software, which automatically inverts the apparent resistivity values to produce two-dimensional resistivity models. At Guenfouda, the results revealed a resistant basement at around 5 m depth overlain by conductive layers, with high-resolution imaging identifying clear subsurface variations and heterogeneities within the cave structure. At Reggada-Jrawa, the survey detected superficial, highly resistive structures about 1 m wide and located at a depth of 1 m, interpreted as remnants of ancient wall foundations belonging to the 10^{th} century Islamic city known from historical sources. Resistivity values ranged from less than 50 Ohm ·m in conductive layers to more than 500 Ohm ·m in resistant structures, confirming strong contrasts between natural deposits and anthropogenic features. This research illustrates the methodological value of multi-resolution ERT for site characterisation and for guiding and optimising future excavation strategies in the Eastern Morocco region.

KEYWORDS: Ancient Habitat Structures, Applied Geophysics, Archaeological Prospection, Eastern Morocco, Electrical Tomography, Heritage Conservation, Subsurface Imaging.

[FR] La tomographie de résistivité électrique (ERT) représente une méthode géophysique non-invasive essentielle pour la prospection archéologique avant et pendant les fouilles. Elle permet aux archéologues d'investiguer les structures souterraines, de délimiter les zones d'intérêt et de réduire les fouilles destructrices en fournissant des images à haute résolution des vestiges enfouis. Cette étude démontre l'efficacité de l'ERT pour détecter des structures archéologiques enfouies sur deux sites majeurs de l'Est du Maroc: la grotte de Guenfouda (province de Jerada) et le site de Reggada-Jrawa (province de Berkane). À l'aide d'un système Syscal Pro équipé de 24 électrodes actives en configuration dipôle-dipôle, cinq profils de résistivité ont été réalisés avec des espacements d'électrodes variables (0,5 m, 1 m, 2 m et 5 m) permettant d'atteindre des profondeurs d'investigation allant d'environ 2 m à 25 m. Les données ont été traitées avec le logiciel Res2Dinv, qui inverse automatiquement les valeurs de résistivité apparente pour produire des modèles de résistivité en deux dimensions. À Guenfouda, les résultats ont révélé un substratum résistant à environ 5 m de profondeur recouvert par des couches conductrices, avec une

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imagerie haute résolution identifiant des variations et des hétérogénéités claires dans la structure de la grotte. À Reggada-Jrawa, la prospection a détecté des structures superficielles fortement résistives d'environ 1 m de largeur et situées à 1 m de profondeur, interprétées comme les vestiges de fondations de murs anciens appartenant à la ville islamique du Xe siècle connue par les sources historiques. Les valeurs de résistivité variaient de moins de 50 Ohm·m dans les couches conductrices à plus de 500 Ohm·m dans les structures résistantes, confirmant de forts contrastes entre dépôts naturels et structures anthropiques. Cette recherche illustre la valeur méthodologique de l'ERT multi-résolution pour la caractérisation des sites et pour orienter et optimiser les futures stratégies de fouilles dans la région de l'Est du Maroc.

MOTS CLÉS: Conservation du patrimoine, Géophysique appliquée, Imagerie du sous-sol, Maroc oriental, Structures d'habitats anciens, Tomographie électrique.

التصوير المقطعي المُحَوْسَب (أداة جيوفيزيائية) في خدمة علم الآثار: أمثلة من مواقع اثرية بشرق المغرب **[AR]**

تُعد المقاربة الجيوفيزيائية (التصوير المقطعي) أداة موثوقة للتحري، تُستخدم قبل وأثناء أعمال الحفر. تتيح المسوحات الجيوفيزيائية رسم خرائط للخصائص الفيزيائية للطبقات تحت السطحية خلال عمليات الاستكشاف الواسعة النطاق. وتُعد تقنية التصوير المقطعي للمقاومة الكهربائية (ERT) واحدة من أكثر التقنيات استخداماً في الرفع الجيوفيزيائي. تم تحديد هذه الدراسة الجيوفيزيائية مسبقاً لتقديم الدعم للأثريين في تخطيط الحفريات المستقبلية، وللتحقق مما إذا كانت المواقع التي تم اكتشافها سابقاً لا تزال تحتوي على بقايا مهمة تحت السطح. وقد تم تنفيذ مسح ثنائي الأبعاد (ERT) في موقعين أثريين يقعان في الجهة الشرقية من المغرب (غنفودة ورڭادة–جراوة)، على مقربة من مدينة وجدة. وقد أُجري المسح باستخدام نظام Syscal Proالمزود بـ ٢٤ إلكترود نشط. وتم اختيار شبكة "ثنائي القطب – ثنائي القطب" لإجراء القياسات نظراً لحساسيتها العالية للتغيرات الأفقية في المقاومة الكهربائية. تم استخدام برنامج Res2dinv لعكس بيانات المقاومة الظاهرة تلقائياً وإنشاء نموذج ثنائي الأبعاد للمقاومة. في مغارة قنفودة (إقليم جرادة)، أُجري المسح باستخدام تباعد بين الإلكترودات بمقدار ١ متر و٠,٥ متر؛ بينما كانت أطوال المقاطع ٢٣ متراً و١١,٥ متراً على التوالي، وقد تم الوصول إلى أعماق تبلغ ٥ أمتار و٢ متر على التوالي. تُظهر القطاعات تباينات كبيرة في المقاومة الكهربائية أفقياً وعمودياً: حيث توجد طبقة عالية المقاومة تقع مباشرة فوق الطبقة تحت السطحية، تغطي طبقة موصلة وصخوراً قاعدية مقاومة. أما في موقع رڭادة–جراوة (إقليم بركان)، فقد تم إجراء المسح باستخدام تباعد بين الإلكترودات بمقدار ٥ أمتار، و٢ متر، و١ متر، بهدف الوصول إلى أعماق ٢٥ متراً، و١٠ أمتار، و٥ أمتار على التوالي. ويُظهر أول متر تحت السطح وجود بنيات ذات مقاومة عالية بعرض متر واحد، قد تكون بقايا لجدران قديمة.

الكلمات الدالة: بُنى سكنية قديمة، التصوير المقطعي الكهربائي، التصوير تحت السطحي، التنقيب الأثري، الجيوفيزياء التطبيقية، الحفاظ على التراث، شرق المغرب.

I.INTRODUCTION

Applied geophysics plays a pivotal role in the non-invasive investigation and characterization of archaeological sites, providing essential information for target assessment during excavation campaigns. The primary goal is to identify and inventory archaeological sites through predictive surveys and to characterize subsurface features with high precision. This enables archaeologists to optimise excavation strategies by focusing on areas of maximum interest, thus improving the efficiency and effectiveness of field operations[1] Archaeogeophysics is fundamentally fundamentally relies on detecting contrasts in physical properties between archaeological structures and their surrounding materials. Buried remains often induce measurable anomalies at the surface, such as variations in electrical resistivity, magnetic susceptibility, or dielectric properties, which can be exploited to infer the presence and geometry of subsurface features. A wide range of geophysical methods has been successfully applied in

[1] GETANEH *et Al*. 2018; HEGYI *et Al*. 2019; MANATAKI *et Al*. 2021; MARTORANA *et Al*. 2023; PEREZ-RODRIGUEZ *et Al*. 2023; BIANCO *et Al*. 2024.

archaeological investigations, including electrical resistivity, magnetometry, ground-penetrating radar (GPR), electromagnetic induction, micro-gravity and seismic techniques[2] Geophysical surveys offer higher spatial resolution (increased data density per unit area) and improved sensitivity to subtle subsurface variations, all whilst benefiting from steadily decreasing operational costs, thus making these technologies increasingly accessible for archaeological research.

Amongst these methods, ERT has emerged as one of the most widely used techniques for high-resolution imaging of the shallow subsurface. ERT enables the construction of 2D and 3D models of subsurface resistivity distributions, providing critical insights into the geometry and composition of buried structures. This method has proven highly effective in archaeological prospecting, particularly as a diagnostic tool to delineate priority zones for surface surveys and targeted excavations[3]. In this study, we present the application of ERT to two archaeological sites in northeastern Morocco: Guenfouda and Reggada-Jrawa. The objective is to demonstrate how ERT can effectively support archaeological investigations by providing non-invasive, high-resolution imaging of buried structures.

II. ARCHAEOLOGICAL SITES OF GUENFOUDA AND REGGADA-JRAWA

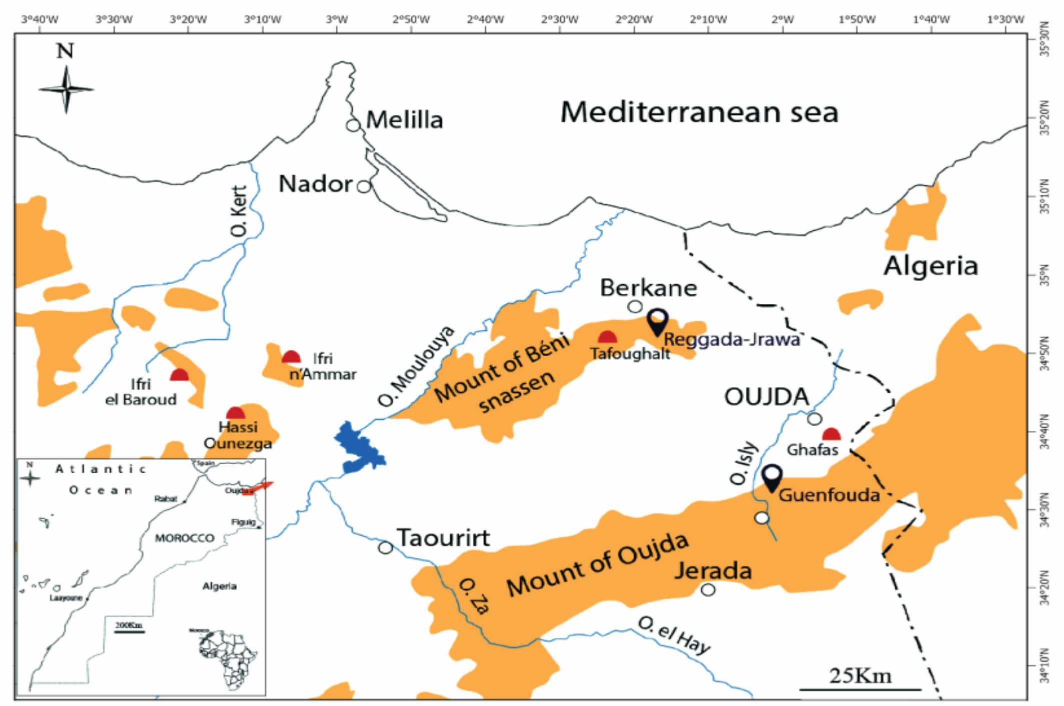
The Guenfouda site is a cave located in the Horst belt of northeastern Morocco, about 30 km south of Oujda city [**FIGURES 1-2**]. It has yielded a rich and varied assemblage of archaeological materials preserved within several stratified layers[4] .The Reggada-Jrawa site, as reported in historical texts[5], corresponds to an Islamic city dating back to the 10th century, characterized by the presence of a Kasbah. It is located in Oujda Basin, approximately midway between the cities of Ahfir and Berkane, near the small village of Aïn Reggada **[FIGURE 1]**. Archaeological material, particularly ceramics, was uncovered during our investigations.

[2] BATAYNEH *et Al*. 2007; MÜLLER *et Al*. 2009; ZHAO *et Al*. 2013; RABBEL *et Al*. 2014; DI MAIO *et Al*. 2016; FLORIO *et Al*. 2019; LULEWICZ *et Al*. 2019; ORLANDO *et Al*. 2019.

[3] LEUCCI *et Al*. 2007; LEOPOLD *et Al*. 2010

[4] AOURAGHE *et Al*. 2008.

[5] MADANI 2015.



[FIGURE 1]: Location of the Guenfouda and Reggada-Jrawa sites (Eastern Morocco)

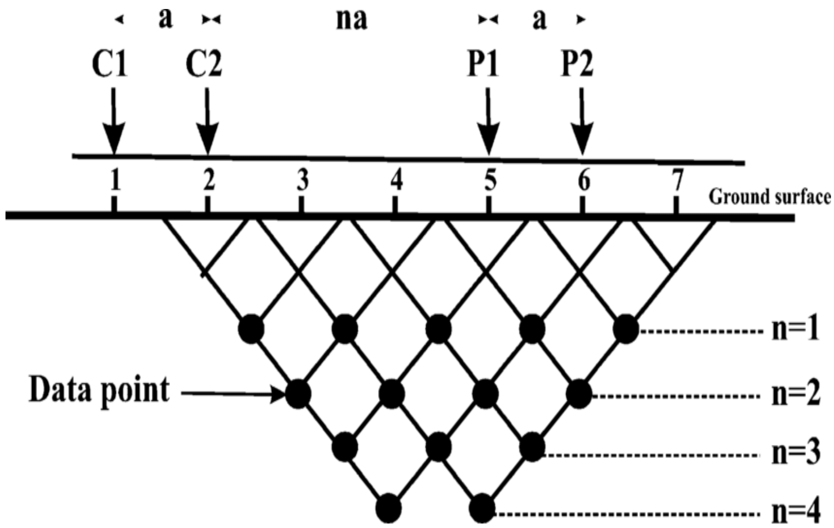
[FIGURE 2]: Guenfouda cave (Province of Jerada)

[FIGURE 3]: Measurement protocol inside the Guenfouda cave

III.DATA ACQUISITION

ERT is a geophysical imaging technique used to measure the electrical resistivity of subsurface materials and generate detailed images of underground structures[6]. The method consists of deploying an array of electrodes along a profile or grid to detect spatial variations in resistivity, which reflect differences in subsurface composition and structure. The principle of the method is based on Ohm's law: a controlled current (I) is injected into the ground through two current electrodes (C1 and C2), and the resulting potential difference (ΔV) is measured between two potential electrodes (P1 and P2). From these measurements, the apparent resistivity (ϱa) is determined using the formula: **$\varrho a = K \times \Delta V / I$**

Where K is the geometric factor that depends on the electrode configuration. In this study, the dipole–dipole electrode configuration was adopted because of its high sensitivity to lateral resistivity contrasts **[FIGURE 4]**, making it particularly effective for identifying discrete archaeological features such as walls, voids and buried foundations[7].



[FIGURE 4]: Configuration of the four-electrode DC dipole–dipole array used for resistivity profiling C1 and C2 denote the current electrodes, P1 and P2 the potential electrodes. The electrode spacing is a, and the dipole separation equals n × a (with n ranging from 1 to 6). Electrode stations were positioned at 1–7 m intervals along the profile

ERT survey was carried out using the Syscal Pro system with 24 active electrodes [FIGURE 4]. Field measurements, acquired with a dipole–dipole array, were processed using Res2Dinv software, which applies automatic inversion algorithms to transform apparent resistivity data into accurate two-dimensional resistivity models. This approach provides reliable imaging of the subsurface, facilitating archaeological interpretation.

Five ERT profiles were conducted across the two archaeological sites: two profiles in the Guenfouda cave and three profiles at the Reggada-Jrawa site. The characteristics

[6] KHATTACH *et Al.* 2025.
[7] GAFFNEY *et Al.* 2015; BINLEY *et Al.* 2020; BLANCHY *et Al.* 2020; DORO *et Al.* 2022; CRISTINO *et Al.* 2024.

and specifications of these profiles, including number and electrode spacing, are summarized in **[TABLE 1]**.

The electrode separation directly influences the depth of penetration and resolution of the ERT survey. Larger spacing increase depth of investigation but reduce lateral resolution, while smaller spacing enhance near-surface resolution at the expense of depth. In this study, the electrode spacing was selected as a compromise to ensure sufficient depth to image archaeological remains while maintaining high resolution to detect narrow structures such as walls and voids.

Profile N°	Number electrodes	Spacing	Array
Guenfouda1	24	1	Dipole-Dipole
Guenfouda2	24	0.5	Dipole-Dipole
Reggada1	24	5	Dipole-Dipole
Reggada2	24	2	Dipole-Dipole
Reggada3	24	1	Dipole-Dipole

[TABLE 1]: Characteristics of electrical profiles.

IV. DISCUSSION

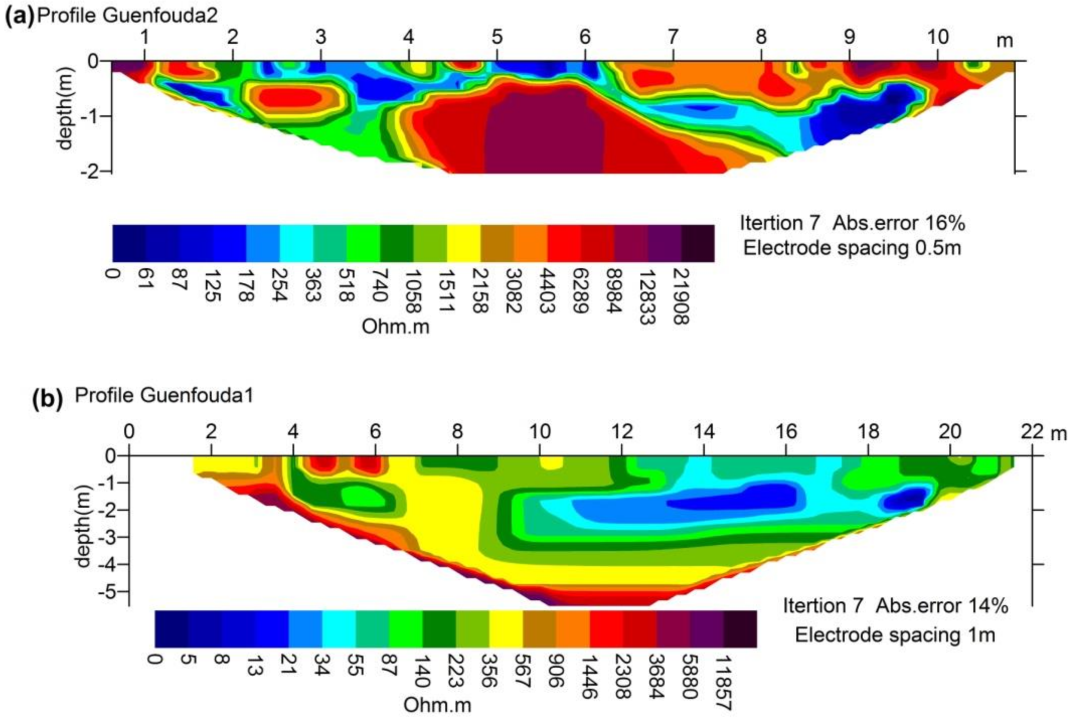
A. Guenfouda Site

Profile Guenfouda1, with 23m length and 1m electrode spacing, reveals significant lateral and vertical resistivity variations extending to 5m depth **[FIGURE 5/B].** The section demonstrates a complex subsurface structure characterized by a highly resistant basement (>500 Ohm.m) at approximately 5m depth, overlain by a sequence of alternating conductive and resistive layers.

A particularly notable feature is a very conductive layer (<50 Ohm.m) approximately 2m thick, positioned at 2-3m depth. This low-resistivity zone may indicate the presence of moisture-rich sediments or organic-rich archaeological deposits, common in cave environments with prolonged human occupation.

Profile Guenfouda2 focuses on the uppermost 2m of the subsurface using 0.5m electrode spacing for enhanced resolution **[FIGURE 5/A].** This detailed imaging reveals several significant features:

- A highly resistive anomaly between x=4m and x=6m, with its top surface at 0.5m depth, possibly indicating stone structures or consolidated archaeological deposits;
- An extensive high-resistivity layer between x=6m and x=11m, approximately 1m thick, potentially representing a prepared floor surface or structural foundation;
- These resistive features are overlain by a thin conductive layer, likely representing recent sediment accumulation.



[FIGURES 5/A-B]: Resistivity sections conducted in Guenfouda site. A. Guenfouda2 corresponds to the first part of the Guenfouda1 (x=0 to 11m) with an electrode spacing of 0.5m. B. Profile Guenfouda1 with an electrode spacing of 1m.

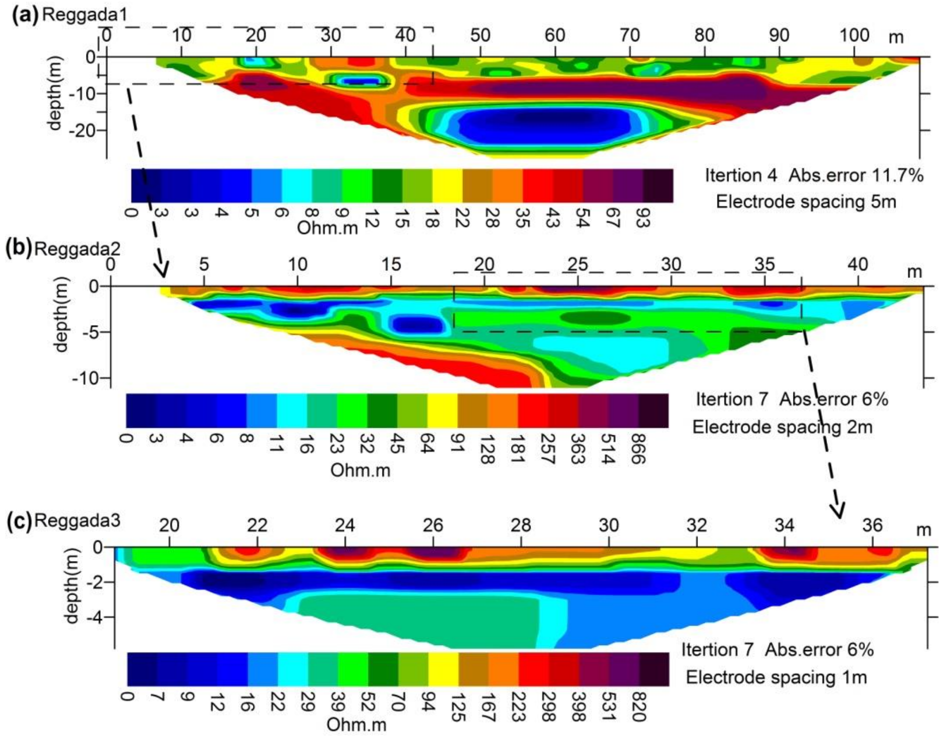
B. Reggada (Jrawa) Site

Three profiles have been carried out in the site of Reggada- Jrawa **[FIGURE 6]**. The long-range profile Reggada1, extending 115m with 5m electrode spacing, provides regional geological context to 25m depth **[FIGURE 6/A]**. The section reveals the broader geological framework, showing a succession of conductive and resistive layers reflecting lithological variations. From bottom to top, the sequence consists of:

- Deep conductive basement (possibly clay-rich formations)
- Intermediate resistive layer (potentially consolidated sediments or bedrock)
- Upper zone with variable resistivity related to surface geology and potential archaeological features.

Profile Reggada2 examines the first 46m of Reggada1 with 2m electrode spacing, providing detailed imaging to 10m depth [**FIGURE 6/B**]. This intermediate-scale survey reveals the transition from regional geological patterns to more localised archaeological features, showing the upper resistive layer in greater detail and identifying potential zones of archaeological interest. The focused high-resolution survey Reggada3 covers the zone from x=18m to x=37m with 1m electrode spacing [**FIGURE 6/C**]. This detailed investigation reveals the most archaeologically significant results:

- A superficial resistive layer approximately 1m thick overlying a relatively conductive substrate
- Discrete high-resistivity structures with characteristic widths of ~1m within the upper layer
- These resistive anomalies are interpreted as remnants of ancient wall foundations, consistent with the site's identification as a 10th-century Islamic settlement.



[FIGURES 6/A-C]: Resistivity sections conducted in Reggada-Jrawa site. A. Profile Reggada1 with an electrode spacing of 5m. B. Reggada2 corresponds to the first part of the Reggada1 (x=0 to 46m) with an electrode spacing of 2m. C. Reggada3 is focused on the part between x=18 et x= 37m of Reggada2, it shows superficial very resistive structures which would correspond to residues of wall foundations.

C. Discussion

This study presents a preliminary geophysical survey conducted at the archaeological sites of Guenfouda and Jrawa (Reggada) in northeastern Morocco, aimed at delineating subsurface structures using the ERT method. The resistivity variations revealed distinct anomalies: high-resistivity zones likely correspond to remnants of ancient walls, structural foundations, or consolidated archaeological deposits, while low-resistivity zones may indicate graves or features filled with loose, water-saturated sediments. The resistivity values and structural dimensions are consistent with stone foundation construction typical of medieval Islamic architecture in the region (Jrawa site).

The results confirm the ability of ERT to distinguish lithological variations from anthropogenic structures, offering valuable insights for archaeological interpretation. The anomalies correspond well with subsurface patterns expected in sites of this type, supporting the reliability of geophysical prospection in guiding excavation strategies. Beyond identifying discrete structures, the survey also provided a broader view of site stratigraphy, revealing contrasts between natural deposits and cultural layers. Comparable applications of ERT in Morocco[8] , and elsewhere demonstrate the growing role of geophysical tomography in archaeology, particularly when combined with other methods.

[8] EL KHAMMARI *et Al*. 2007; WAFIK *et Al*. 2023.

Overall, this study highlights the potential of ERT as a non-invasive and cost-effective tool for archaeological research in northeastern Morocco. By detecting both structural remains and possible burial features, the method enhances site characterization and helps prioritise areas of highest archaeological significance for future excavations. These results open promising perspectives for integrating ERT with complementary geophysical techniques to further refine the investigation of ancient settlement structures.

V.CONCLUSION

This study highlights the significant potential of multi-resolution ERT for archaeological prospection in northeastern Morocco. By integrating regional geological characterization with high-resolution imaging of subsurface features, ERT has proven effective in identifying buried archaeological structures. Geophysical surveys were conducted at two key sites: Guenfouda and Reggada-Jrawa. At Guenfouda, ERT data revealed a resistant basement at approximately 5 metres depth, while at Reggada-Jrawa, shallow, highly resistive anomalies were identified and interpreted as possible wall foundations, suggesting an Islamic occupation dating back to the 10^{th} century. The dipole-dipole array configuration used was particularly well-suited to the local geological conditions.

These findings demonstrate the practical value of ERT in excavation planning, heritage conservation, and prioritization of archaeological research. Although preliminary, the results provide a solid foundation for future investigations that combine ERT with ground-truth validation and 3D imaging to improve the understanding of archaeological sites across North Africa.

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