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Integrated geophysical techniques for archaeological exploration of subsurface tombs in Saqqara necropolis, Giza, Egypt

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In this study, we investigate the subsurface archaeological features at the Saqqara necropolis, Giza, Egypt, using an integrated geophysical approach combining Seismic Refraction Tomography (SRT), Electrical Resistivity Tomography (ERT), and Ground Penetrating Radar (GPR). The aim is to identify potential buried structures, including tombs and burial chambers, within this historically significant site, which dates to the New Kingdom and earlier periods. SRT provided insights into deeper geological variations, while ERT distinguished anthropogenic features from natural formations and provided further clues about construction techniques. GPR delivered high-resolution imaging of near-surface structures, revealing walls, voids, and architectural elements. The integrated dataset identified anomalous structures at depths of 2–4 meters, including potential chambers, walls, and enclosed spaces resembling rooms. These findings enhance understanding of Saqqara's archaeological landscape and highlight the effectiveness of integrated geophysical surveys in heritage exploration. The results offer valuable guidance for future excavations and underscore the necessity of advanced geophysical techniques in uncovering buried historical narratives at this culturally rich necropolis.

The Saqqara necropolis, nestled on the west bank of the Nile, stands as one of Egypt's most extraordinary archaeological treasures. It has long captivated researchers and history enthusiasts alike, offering a unique window into ancient Egyptian life. Spanning over 7 kilometres, Saqqara served as the burial ground for Memphis, Egypt's ancient capital, and is renowned as the largest and oldest burial site in the country. The site is perhaps most famous for the Step Pyramid of Djoser, a groundbreaking monument designed by the genius architect Imhotep during the Third Dynasty, around 2700 BCE. This pyramid, the first colossal stone structure ever built in Egypt, marked a new era in architecture and continues to inspire awe[1,2].

However, Saqqara is so much more than just the Step Pyramid. It is home to an array of tombs, temples, and burial complexes that stretch across more than 3000 years, reflecting different phases of Egypt's history from the Early Dynastic Period through the Ptolemaic and Roman eras. The necropolis has been the final resting place for kings, queens, and high-ranking officials, its tombs evolving alongside Egypt's changing beliefs about the afterlife. These structures, ranging from the simple, early mastaba tombs to more elaborate pyramid complexes, provide incredible insight into the lives and deaths of Egypt's elite. Many of the tombs are adorned with detailed carvings and colourful paintings, bringing to life the society and politics of ancient Egypt in a way that words alone cannot[3–6].

Over the years, Saqqara has revealed countless extraordinary discoveries, from the tombs of powerful officials to stunning burial chambers filled with intricate artwork. There's even an animal necropolis and the Serapeum, a grand burial site for sacred bulls. Yet, despite its rich history of exploration, so much of Saqqara remains a mystery[7]. Large portions of the site are still unexcavated, waiting patiently to tell their stories. This is why Saqqara continues to be a critical area for archaeological research.

Traditional excavation methods can be risky, especially for a site as delicate and complex as this one. This is where modern technology steps in. With so much hidden beneath the sand, non-invasive techniques have become essential tools in uncovering Saqqara's secrets while preserving its integrity[8].

Selecting the appropriate geophysical method depends on the survey site characteristics and objectives, as each technique highlights different physical contrasts as shown in Table 1. Additionally, careful consideration of spatial and temporal sampling intervals is essential for achieving the desired depth penetration and resolution, informed by an understanding of the target's nature and size relative to the surrounding medium[9]. The study area was selected based on prior surveys conducted by Ian Mathieson between 1990 and 2009, called the Saqqara Geophysical Survey Project (SGSP)[10].

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Table 1 | Geophysical techniques employed in environmental and archaeological exploration modified after G. El-Qady et al. [9]

Technique	Sensitive property	Vertical resolution	Horizontal resolution	Application[a]
Thermal	Thermal conductivity	Poor	Moderate	Yes
Magnetic	Magnetic susceptibility	Moderate	Good	Yes
Gravity	Density	Moderate	Moderate	Rarely
Self-potential	Electrokinetic effect	Moderate	Moderate	No
Electrical resistivity	Electrical resistivity	Moderate	Good	Yes
Electromagnetic	Electrical resistivity	Moderate	Good	Yes
Induced polarization	Electrical chargeability	Moderate	Moderate	No
GPR	Dielectric permittivity	Good	Good	Yes
Seismic	Seismic velocity/ density	Good	Good	Yes

[a]Application in Environmental and Archaeological explorations.

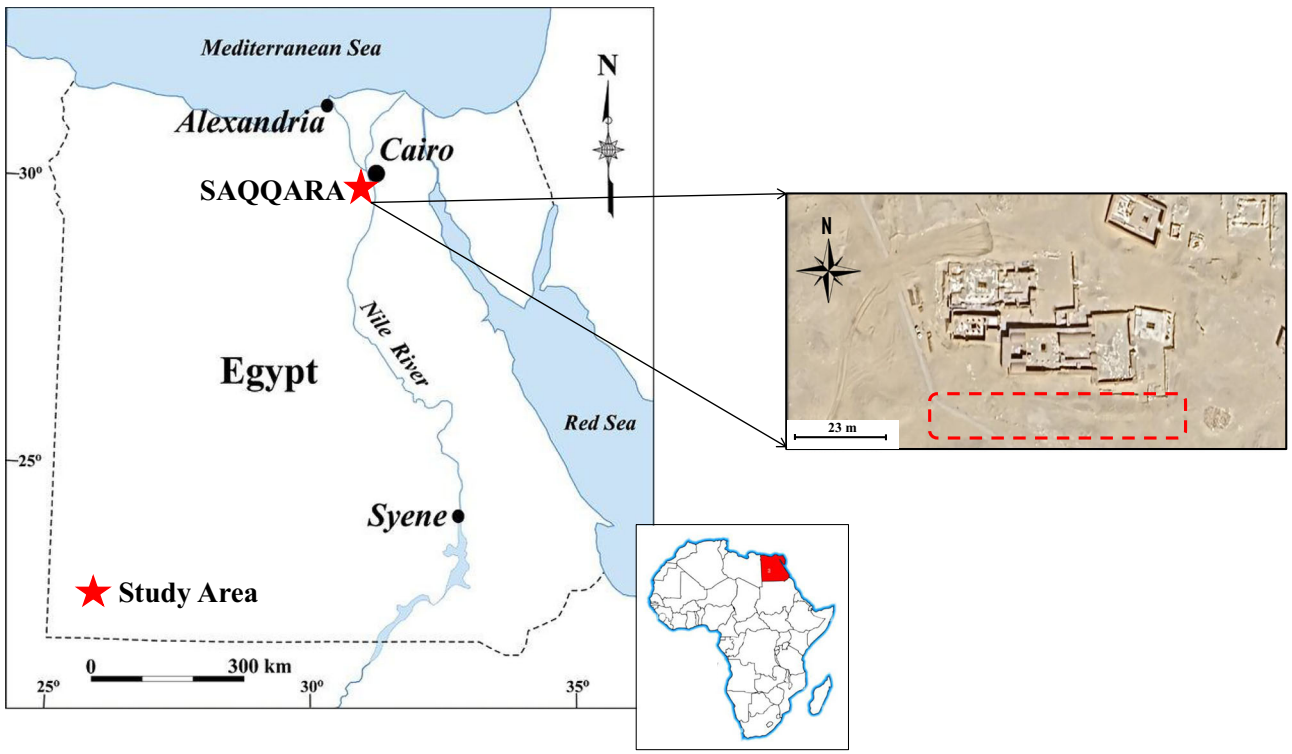


Fig. 1 | The map of Egypt shows the Location of the survey area projected on Google Maps (Image generated using Google Earth Pro). The red rectangle shows the area of the initial survey.

In this study, we've used three geophysical techniques: SRT, ERT, and GPR, according to the previous table. Each of these methods brings its strengths. Seismic Refraction helps us understand the bedrock in the study area. GPR offers sharp images of near-surface features like walls and voids, and ERT allows us to detect different materials by mapping their resistivity, which helps identify structures made of materials like mud brick or limestone. Together, these techniques create a detailed picture of what lies hidden underground[4,11–21].

Since the groundbreaking magnetic survey conducted in 1987, geophysical investigations have played a pivotal role in advancing archaeological research in the Saqqara region[22]. This initial exploration aimed to locate potential subterranean burial complexes, and in 2004, it culminated in the extraordinary discovery of the richly decorated tomb of Merefnebef, a high-ranking official from the late Old Kingdom period[23]. Building on this achievement, the Saqqara Geophysical Survey Project (SGSP) continued in 2012, significantly enhancing our understanding of the Saqqara necropolis. These surveys revealed hundreds of previously unknown buried structures spanning various historical eras, shedding light on the intricate spatial organization and the chronological evolution of this iconic archaeological site. Such findings have not only deepened our comprehension of Saqqara's historical significance but have also underscored the transformative impact of geophysical techniques in uncovering Egypt's ancient past[24].

Also, in the 2012 field campaign, the Polish Egyptian archaeological team employed Ground Penetrating Radar (GPR) to explore the subsurface of the West Saqqara region, aiming to uncover sepulchral structures. The survey identified three primary types of archaeological features: burial shafts, mobile bodies (solid rock blocks from tombs), and sarcophagi containing mummies[25].

The importance of these non-invasive methods was underscored by the discovery of the tomb of "Iwrhya," an official who served under the famous pharaohs Seti I and Ramesses II. This incredible finding, made during the first phase of our project at the Cairo University concession (The Unas Pyramid South)[4], shows just how powerful combining geophysics with archaeology can be. By minimizing the need for digging, we can preserve the fragile structures of Saqqara while still uncovering new layers of its history.

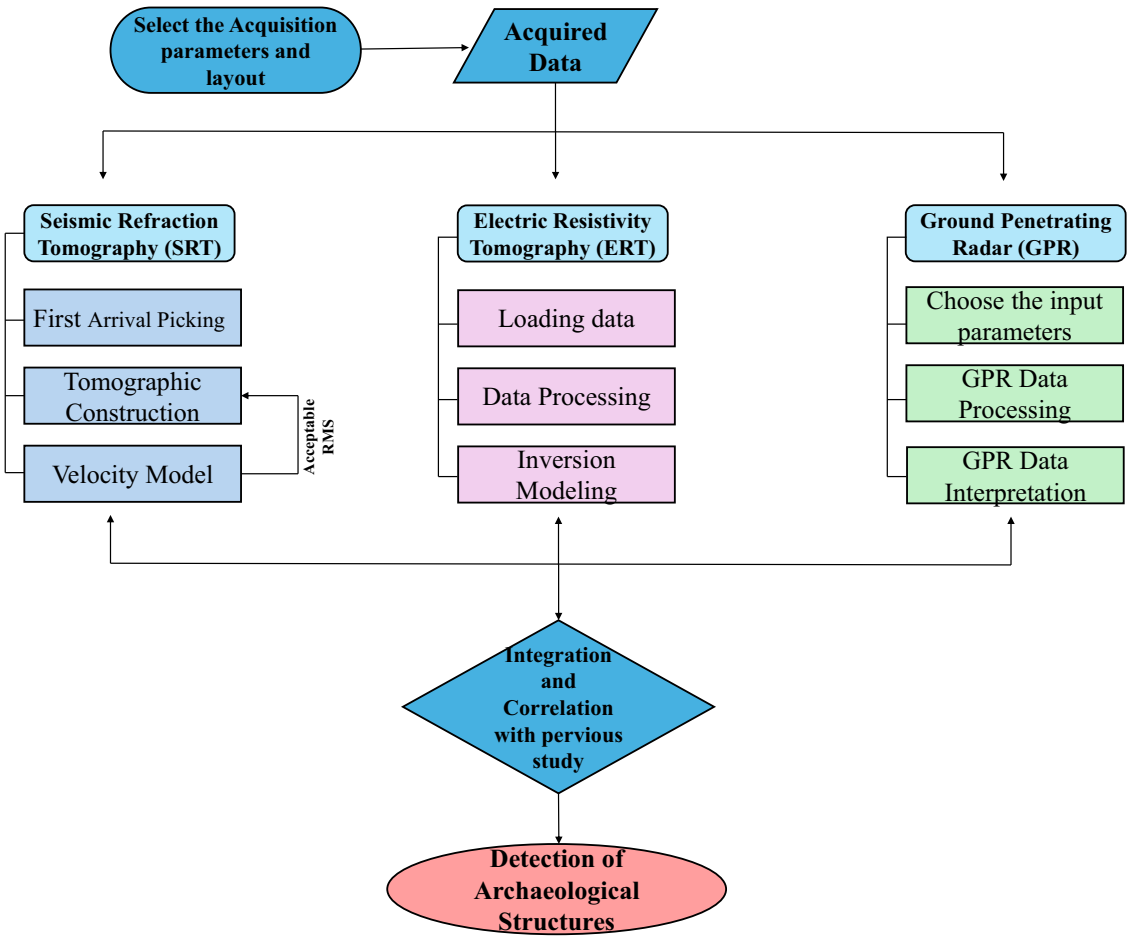


Fig. 2 | The flowchart represents the workflow of the three geophysical techniques and their integration for joint interpretation. The flowchart illustrates the step-by-step followed for the used geophysical techniques. (Created by the authors using Microsoft PowerPoint).

This current phase of the project builds on that success, once again proving the value of these advanced techniques. Through careful mapping of the subsurface features, we're not only adding to our knowledge of Saqqara but also protecting its delicate and irreplaceable heritage. The discoveries we've made help piece together ancient Egypt's architectural and cultural practices, allowing us to walk in the footsteps of the past while ensuring this remarkable site is preserved for future generations.

The Saqqara necropolis, located about 15 km southwest of Cairo on the western bank of the Nile, is one of the world's most important archaeological sites. This ancient burial ground is perched on a gently sloping limestone plateau that rises between 40 and 58 metres above sea level, with an incline of about 5–7° toward the west. The eastern edge of the plateau is sharply defined by a cuesta, marking a natural boundary between the plateau and the Nile floodplain. Geologically, this plateau is composed of carbonate rocks from the Upper Eocene Paleogene period, specifically the Upper Calcareous beds of the Saqqara Member within the Maadi Formation. These layers consist of firm, compact limestone interbedded with softer marly limestone, forming a 22-metre-thick sequence that is characteristic of the area[1,26].

Over millennia, the Saqqara region has seen the accumulation of windblown sands, particularly since the end of the Holocene pluvial period. These aeolian deposits, which range from 0.5 to 3 metres thick, blanket the older geological layers. The region's stratigraphy is further complicated by calcareous debris from the construction of monumental tombs during the Old Kingdom period, around 4600 years ago. This mix of natural sedimentation and human activity has created a complex archaeological landscape, where layers of history are intricately interwoven with the geological past[2,27].

Our study is centred on the Cairo University concession within Saqqara, an area that dates primarily to the New Kingdom (Fig. 1). The site is notable for its tombs, which are aligned along an east-west axis and extend southward, culminating in a prominent hill where older Old Kingdom tombs are located. At the heart of this area lies a large, partially explored mastaba, a type of Old Kingdom tomb offering a glimpse into the region's ancient funerary architecture. Previous investigations in the 1980s faced technological limitations that left many aspects of this significant structure undiscovered, highlighting the need for continued research and advanced techniques[5,26].

Methods

Effective planning for archaeological investigations and restoration efforts requires an in-depth analysis of the structures and monuments uncovered. This includes understanding the building materials and techniques used, mapping patterns of deterioration, identifying damage, and determining the underlying causes[28].

In this investigation, we employed a carefully coordinated method combining three geophysical techniques: SRT, ERT, and GPR to explore specific parts of the Saqqara region (Fig. 2). Each technique was chosen for its specific capabilities to expose subsurface details, ensuring a full assessment of the archaeological findings. This convergence of approaches provides for a fuller understanding of the site's structural composition, guiding both the preservation and future research of these historical remnants.

Seismic refraction tomography (SRT)

In seismic exploration, vibrations are generated, and their arrival times are carefully recorded as they travel from the source to a series of geophones. This method capitalizes on variations in density and elastic properties to interpret subsurface structures by analyzing the travel times of different

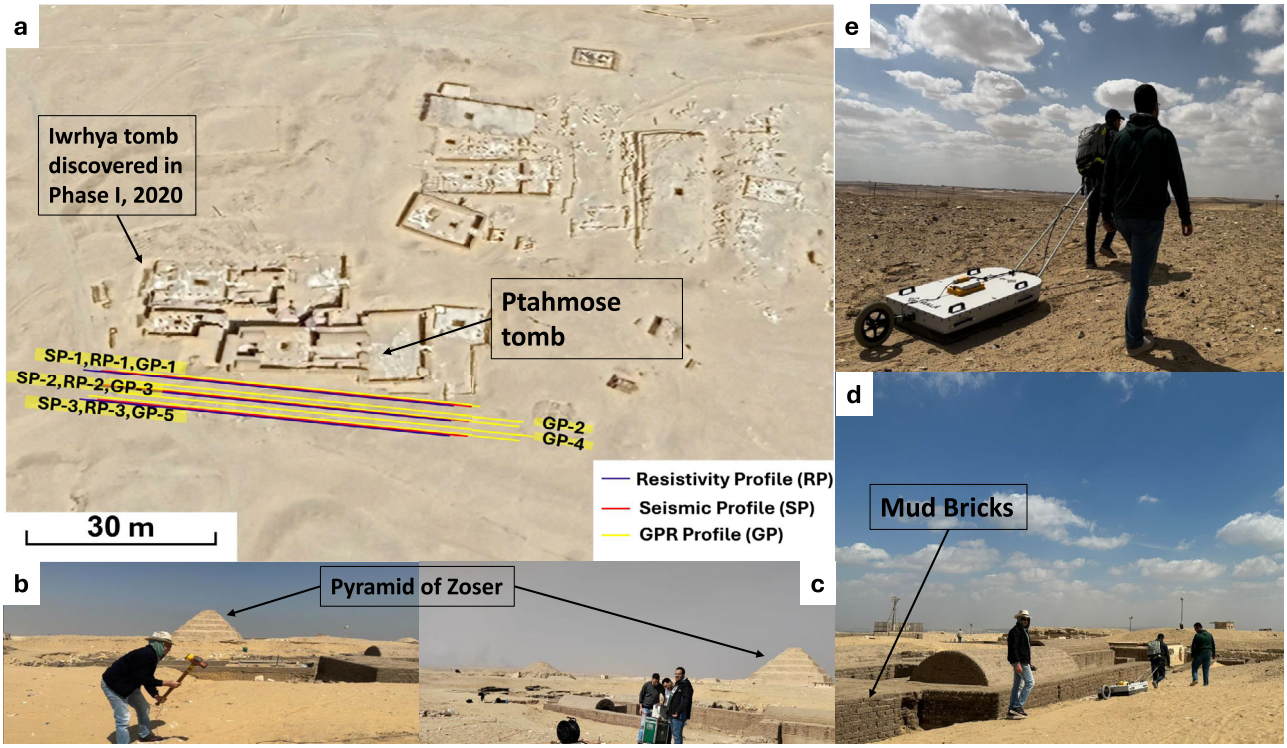


Fig. 3 | Geophysical survey setup and data acquisition strategy in the Saqqara study area. a Map indicating the precise localization of geophysical measurements, including Seismic Refraction Tomography (SRT), Ground Penetrating Radar (GPR), and Electrical Resistivity Imaging (ERT); **b** Seismic data acquisition using a sledgehammer as the se the seismic source; **c** Resistivity data acquisition with the SYSCAL Pro system, utilizing electrodes to measure subsurface potential difference.; **d** and **e** GPR data acquisition using the MALA ProEx with a 100 MHz antenna for detailed subsurface imaging during the survey (Note: walls of the tombs are built up from conductive mud bricks as shown)". All images are original, taken by the authors during the field survey".

wavefronts[12]. SRT is particularly useful for mapping shallow subsurface layers, estimating their thickness, and providing preliminary lithological insights[29]. By detecting contrasts between solid rock and subsurface voids, SRT effectively reveals changes in the mechanical properties of the ground. Unlike other techniques, such as GPR or ERT, seismic surveys are less constrained by site conditions. Seismic signals are less affected by factors like soil conductivity, and they attenuate more slowly, making this approach effective even in challenging environments[11,30–35].

In this study, three linear seismic refraction arrays were deployed to cover the survey area (Fig. 3a), primarily in an east-west direction. Each array featured a consistent 3-metre spacing between geophones, resulting in a total profile length of 72 metres. The data were collected using a multi-channel OYO seismograph (24 channels), equipped with 40 Hz vertical geophones. A rigid steel plate was struck with a 20 kg sledgehammer to serve as a seismic energy source (Fig. 3b).

Seismic data processing was followed to ensure reliable interpretation. First, the arrival times of seismic waves were carefully picked from the recorded data, focusing on the fastest wave paths. Refracted phases were then identified, and travel-time curves were created to estimate the velocities and thicknesses of subsurface layers. The travel-time data were subjected to inversion techniques to construct a velocity model of the subsurface. This model, highlighting seismic velocity variations, provided valuable insights into different geological formations and the structure of the subsurface.

Electrical Resistivity Tomography (ERT)

A powerful tool in archaeological investigations, particularly for detecting subsurface variations in soil or sediment resistivity due to differences in material composition, moisture content, or the presence of buried archaeological features[16]. This method injects electrical currents into the ground through a series of electrodes and measures the resulting potential differences[4]. The data collected creates an apparent resistivity profile, which is used to create the final electrical resistivity tomograms, offering a glimpse into the subsurface. Archaeologists rely on ERT to identify and map features such as walls, foundations, pits, or other anomalous structures that may suggest the existence of archaeological remains. This noninvasive approach provides critical insights into a site's spatial layout, enabling more informed excavation effort planning[36–41].

For our survey, we utilized the SYSCAL Pro Switch unit, equipped with 24 electrodes that automate the switching process for data collection (Fig. 3c). The arrangement and pairing of transmitting and receiving electrodes determine the resolution and depth of the profile. At the same time, the total cable length directly influences the maximum depth of investigation. In this study, we acquired three profiles with a 3-metre electrode spacing to investigate a large target like a room, hall, or chamber and give me more depth of penetrations, yielding a total profile length of 69 metres (Fig. 3a). The dipole-dipole configuration was chosen for its ability to provide higher resolution, particularly in mapping vertical structures, and for its sensitivity to fluctuations in horizontal resistivity[42]. This setup allowed us to reach a penetration depth of approximately 11 to 16 metres, effectively covering the same area as our seismic refraction and GPR surveys.

It's important to note that the resistivity recorded during the survey are 'apparent' resistivity values, rather than the 'true' resistivity of the subsurface[43]. This is because the measurements are influenced by the entire path the current travels between electrodes. An inversion process is applied to convert apparent resistivity into true resistivity. Using RES2DINV inversion software, which employs a smoothness-constrained least-squares method, we iteratively processed the data to generate the best-fit model of the subsurface resistivity distribution. Through this process, we were able to produce detailed and accurate subsurface images, which were invaluable in identifying archaeological features hidden beneath the surface.

In this investigation, we employed a 2D resistivity model using RES2DINV software to capture the resistivity distribution across the survey region, providing an apparent resistivity pseudo-section that corresponded well with the field results. The process of inversion begins with forward

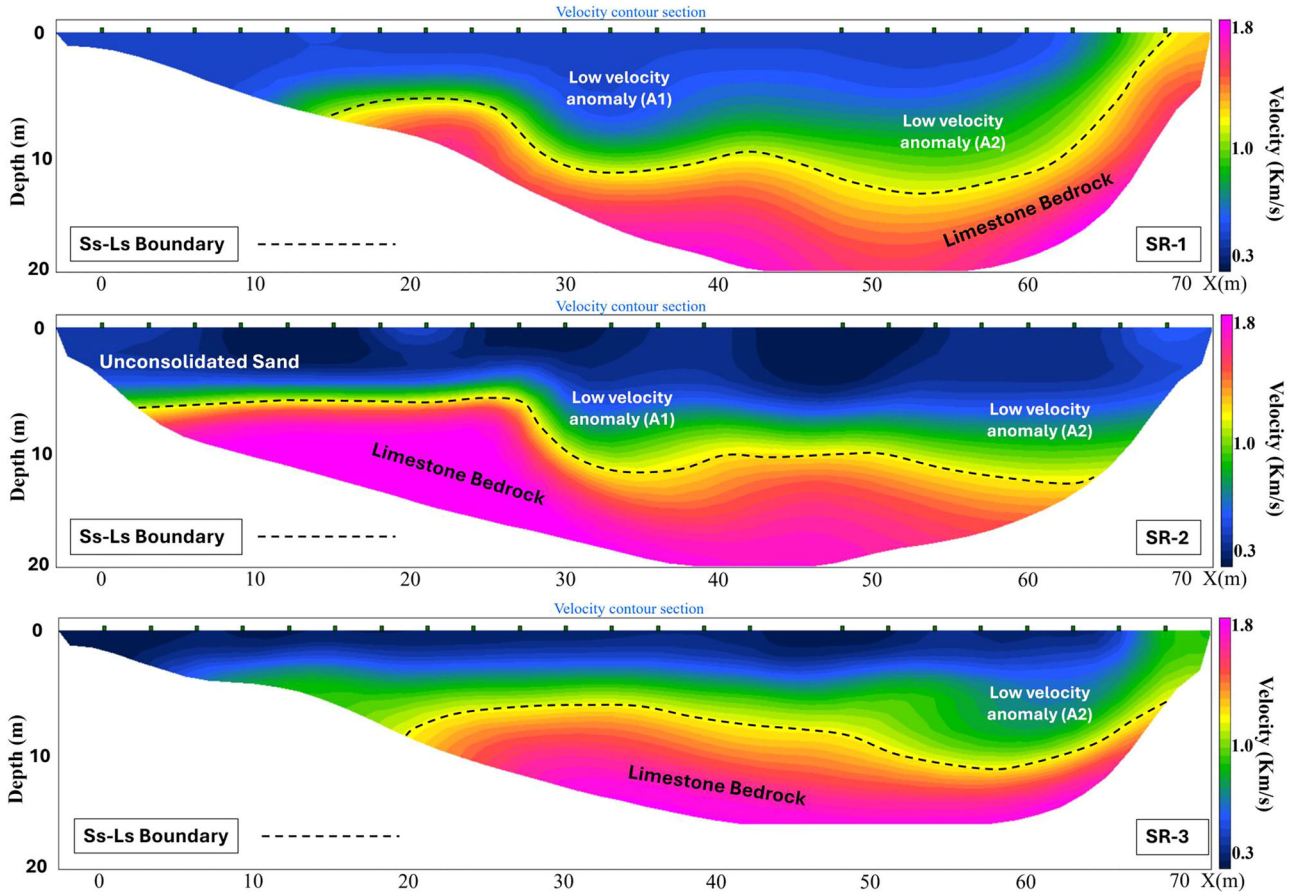


Fig. 4 | Seismic tomographic sections for profiles from SR-1 to SR-3 (By ZondST2D Software). Fig. 2D The results delineate two geo-seismic layers: an upper unconsolidated sand layer and a lower limestone bedrock, separated by the "Ss-Ls Boundary." Two distinctive low-velocity anomalous sources (A1 and A2) are observed. These velocity sources are interpreted as potential archaeological features, as low-velocity zones typically indicate the presence of voids or material disruption, which are commonly associated with human-made structures or artifacts.

modelling to anticipate apparent resistivity values, which are then compared with the actual field data. An iterative procedure is performed to reduce the difference between these anticipated and actual values, expressed as root-mean-square (RMS) error. With each iteration, the original model is updated to reduce the RMS error, ensuring that the final model accurately reflects the genuine resistivity distribution of the subsurface[4,14,44–46].

Ground Penetrating Radar (GPR)

GPR functions by transmitting high-frequency electromagnetic pulses into the ground. When these pulses encounter changes in the subsurface's dielectric properties, such as differences in material composition, portions of the signal are reflected to the surface[47]. A receiver in the radar system detects these reflections, with the strength of the returning signal dependent on the contrast between the subsurface materials. This makes GPR highly effective in mapping subsurface structures without the need for invasive methods[48].

As a non-destructive technique, GPR provides highly detailed images of the subsurface in the form of radargrams. These radargrams allow them to visualize underground features[14]. The method works by capturing electromagnetic pulses, typically in the range of 10 to 2000 MHz, that propagate, reflect, and scatter beneath the surface. A transmitter antenna emits these pulses, while a receiver records both the signal strength and travel time, offering a clear picture of subsurface layers and features[49–51].

One of GPR's main advantages is its superior resolution compared to other near-surface geophysical techniques, such as electrical resistivity. This high-resolution capability allows it to reveal even subtle differences in subsurface materials, making it an invaluable tool for archaeological surveys and other subsurface investigations[16,52–54].

For this study, five profiles of GPR surveys were conducted using a 100 MHz shielded antenna coupled with MALA ProEx GPR equipment (Fig. 3a, d, e). The survey design was carefully crafted to meet depth and resolution requirements. The GPR system was systematically moved across the site layout, collecting data for analysis. However, raw GPR data contains noise and unwanted signals caused by antenna ringing or multiple surface reflections[49]. Therefore, the data underwent a series of processing steps to enhance clarity and usability.

The data processing involved several key steps using EKKO_Project GPR Software V6. The direct-current offset (DC shift) was initially corrected, and background noise was filtered out. The start time of the data was adjusted to remove any extraneous data in front of time zero. A subtract-mean (dewow) filter was applied to eliminate low-frequency noise, followed by a band-pass filter to discard unwanted high-frequency components. Finally, amplitude gain (SEC2) was applied to enhance signal strength, making the radargrams more interpretable. Time depth conversion was done by using velocity = 0.13 m/ns, according to most of the study area being covered with dry soil and sediments (Quaternary deposits) with dielectric constant ranging from (4–6 F/m)[55]. These steps resulted in clear, high-quality subsurface images, offering valuable insights into the buried archaeological features.

In the Saqqara archaeological survey, SRT, ERT, and GPR were chosen for their distinct advantages in detecting subsurface features: SRT excels in revealing deep geological formations, ERT is effective for identifying anthropogenic structures like walls, and GPR provides high-resolution imaging of near-surface features. Despite their strengths, each method has inherent limitations, such as GPR's reduced depth penetration in

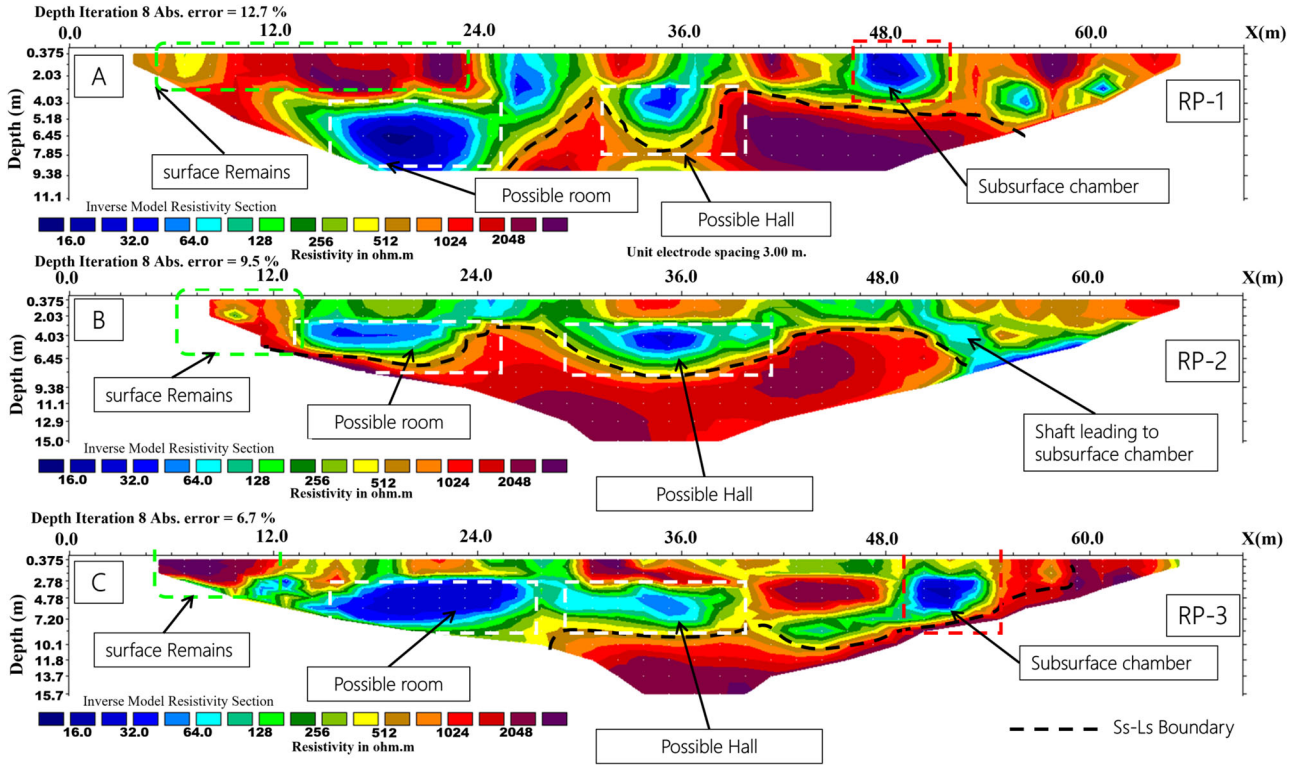


Fig. 5 | Resistivity tomographic sections for profiles from RP-1 to RP-3. Electric Resistivity Inversion along profiles RP-1 to RP-3 are presented as (**A**–**C**) (By RES2DINV Software), marked with potential positions of possible archaeological structures (rooms, halls, walls, and chambers).

conductive soils and ERT's difficulty in resolving deeper structures[56–58]. To overcome these challenges, future research should integrate additional geophysical techniques, such as magnetometry, gravity surveys, and advanced 3D inversion methodologies. This multi-method approach would not only enhance the resolution and depth coverage but also contribute to a more comprehensive understanding of the subsurface, leading to more accurate archaeological interpretations.

Results

This study employs SRT, ERT, and GPR to explore the subsurface for possible archaeological remains. The aim is to detect buried structures, artifacts, or features that could provide insights into past human activities and the area's historical significance. Additionally, geophysical surveys provide valuable information on the ground's geotechnical properties, helping to characterize the nature and composition of subsurface materials, even with limited surface visibility.

This section delves into the outcome obtained from the integration of the results from SRT, ERT, and GPR data interpretation. By synthesizing the data from these methods, we provide valuable insights into the site's geophysical characteristics and archaeological significance. These findings not only enhance our understanding of the subsurface features but also play a crucial role in supporting the preservation and historical interpretation of this culturally rich site. Through this detailed analysis, we aim to guide future exploration and conservation efforts, ensuring that these invaluable remnants are protected and studied for future generations.

Seismic refraction tomography (SRT)

In the surveyed area, the three seismic tomograms reveal two primary seismic strata. These tomograms enabled the calculation of P-wave velocities, layer thicknesses, and the depths of the subsurface rock units. As previously discussed in the geological section, Saqqara is characterized by a limestone plateau overlaid with sandstone sediment. The seismic results identify two distinct geo-seismic layers: an upper sand layer, with velocities ranging from 450 to 1200 m/s and thicknesses between 4 and 11 metres, and a limestone plateau beneath, with velocities ranging from 1200 to 2100 m/s at depths of 4 to 19 metres. A clear boundary exists between these two layers due to the significant contrast in their physical properties, particularly density and velocity (Fig. 4).

The seismic refraction analysis, derived from the tomographic inversion of the first arrivals, also identified two notable low-velocity anomalous sources (A1 and A2), each approximately 4 metres in size. These anomalous sources likely correspond to underground chambers buried beneath the overlying sand in the study area. Anomalous body A1 appears in both Profiles SR-1 and SR-2. Still, it is absent in Profile SR-3, possibly due to the anomalous body's limited horizontal extent or the minimal contrast in physical properties at Profile SR-3, making the feature less detectable.

Considering the lithology of the local formations, coupled with previously excavated archaeological structures in the vicinity, these low-velocity zones are strong indicators of potential archaeological features. Their identification holds considerable significance, as it could guide future excavation efforts and contribute to the broader understanding of the archaeological landscape in Saqqara.

Electrical Resistivity Tomography (ERT)

The study area presents clear evidence of numerous archaeological remains buried at varying depths. These remains probably include tomb structures with interconnected underground burial chambers, walls, or galleries, as suggested by previous excavation work conducted near the site. We interpreted our data according to the archaeological discoveries and findings (approved by actual excavations, El Aguizy et al. [4]) of the surrounding areas and the previous studies. Our interpretation is further guided by the patterns of subsurface anomalous structures observed in the seismic and resistivity data, which align with typical characteristics of human-made structures.

The electrical resistivity data collected at the Saqqara site were processed and inverted using RES2DINV software to generate a resistivity model. The resulting profiles revealed two distinct geological layers (sandstone and limestone), corresponding well with the seismic refraction results. These two layers are separated by a clear boundary (denoted by the black

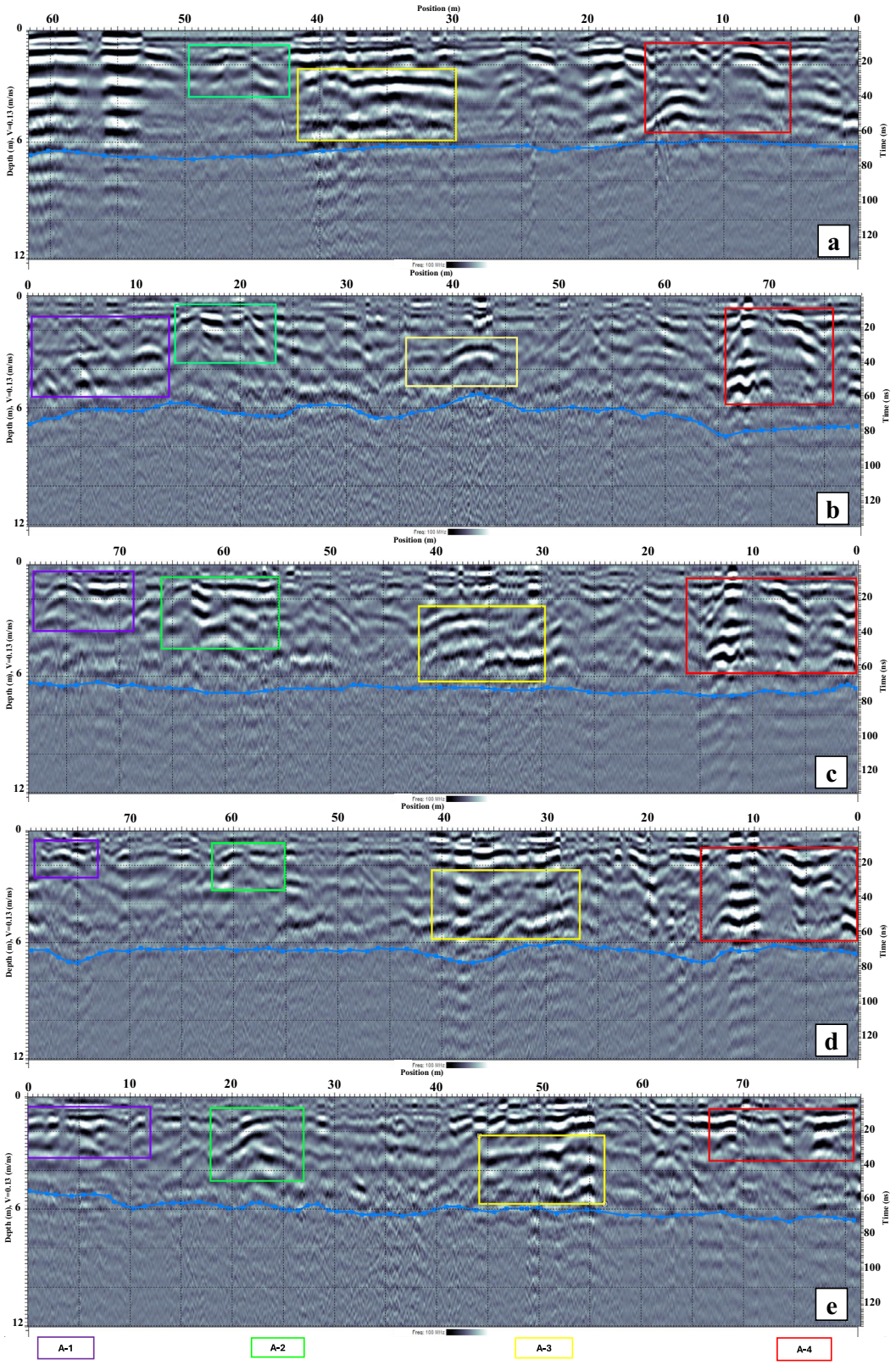


Fig. 6 | Processed and interpreted GPR profiles GP-1 to GP-5. The final processed and interpreted GPR profiles GP-1 to GP-5 are shown as **a**–**e**, respectively (By EKKO_Project GPR Software V6). The blue line indicates the boundary between the first layer (sandstone) and the second layer (limestone). Four main anomalous bodies were identified, A1: A4, indicating different radar signatures.

dashed line), representing the transition between sandstone and limestone (Ss-Ls Boundary) (Fig. 5).

The ERT results also highlighted several persistent sources across all profiles. These low-resistivity sources, ranging in size from 4 to 14 metres and depths from 0.5 to 10 metres, are likely indicative of conductive mud brick structures relative to the resistive dry sand cover. Mud bricks are the dominant structure material in the study area according to the historical era as shown in Fig. 3d, as the low

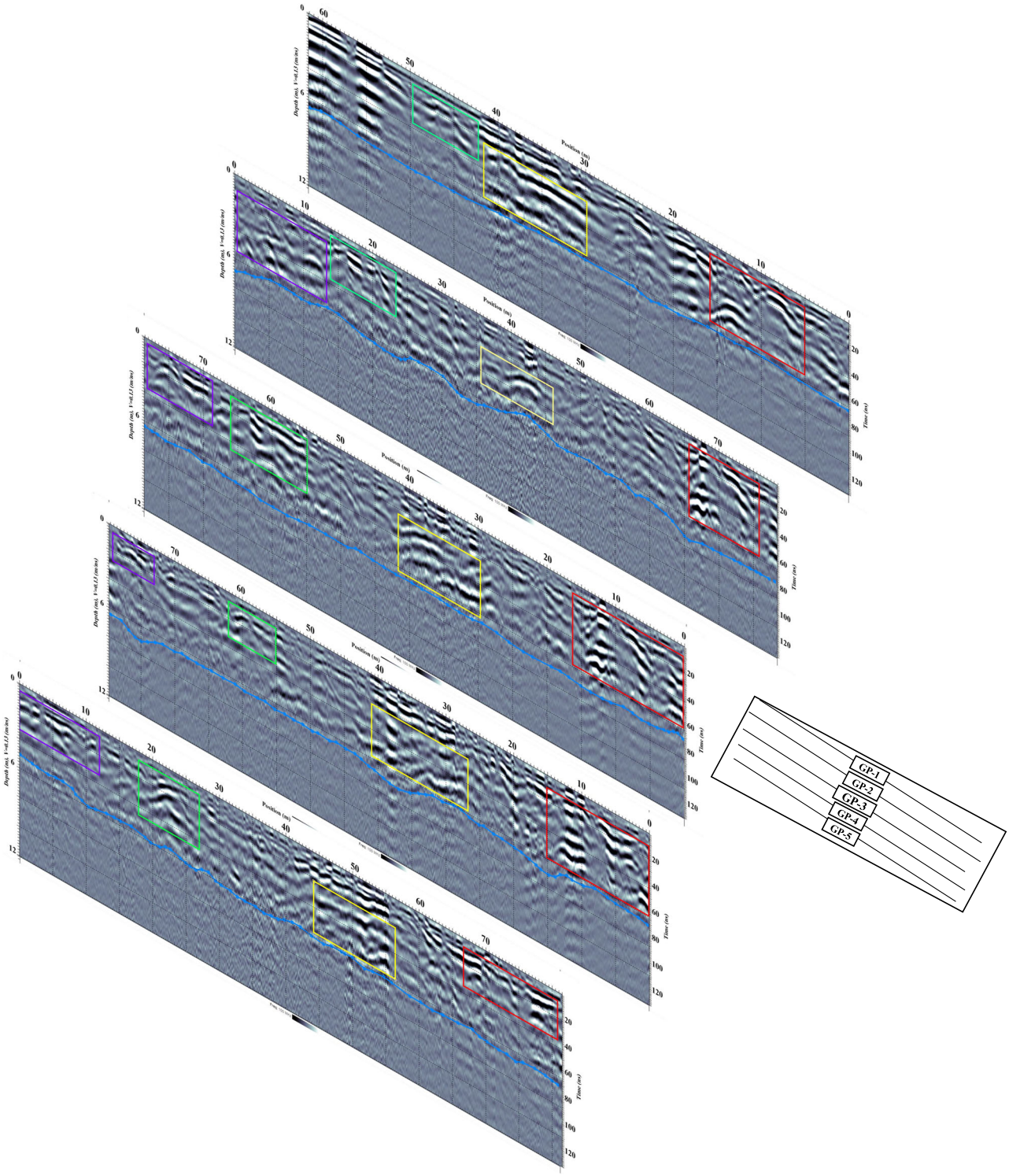


Fig. 7 | Composite visualization of GPR profiles GP-1 to GP-5. The figure shows five parallel GPR profiles (GP-1 to GP-5) with profile spacing of 2 m, are combiened together in a comprehensive visualization according to their position, with the GPR profiles layout (by EKKO_Project GPR Software V6).

resistivity values align with the presence of clay minerals typically found in such materials. These sources are interpreted as potential underground halls, rooms, or archaeological structures, likely buried and covered by surface resistive dry sand sediments.

Ground Penetrating Radar (GPR)

GPR profiles were aligned along the same direction as the seismic refraction and electrical resistivity lines to ensure consistent comparative analysis with the other geophysical methods. The GPR data was processed using EKKO_Project GPR Software V6, yielding more focused and high-resolution subsurface images. These surveys revealed a network of linear features, likely remnants of old walls, roads, or other man-made structures, as indicated by the contrast in electrical properties.

The radargrams revealed two distinct lithological units based on the geology of the study area and changes in the reflectivity pattern: an upper sandstone layer overlying intact limestone, separated by a noticeable

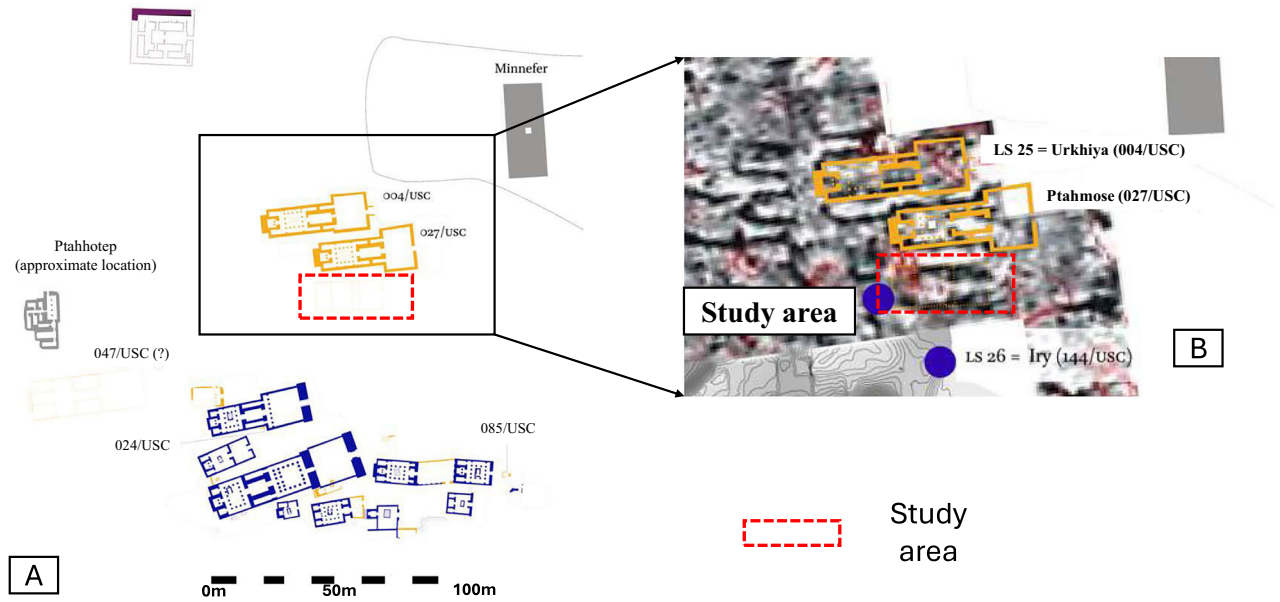


Fig. 8 | Schematic design and magnetic survey results of the area of the Unas Pyramid. A schematic design shows the area of south Unas Pyramid, **B** some magnetic results of the Saqqara Geophysical Survey Project (SGSP), marked with red dashed rectangle represent our study area, adapted from Nico Staring (2023), published under a Creative Commons Attribution License (CC BY-NC-ND 4.0), and used in accordance with the license terms.

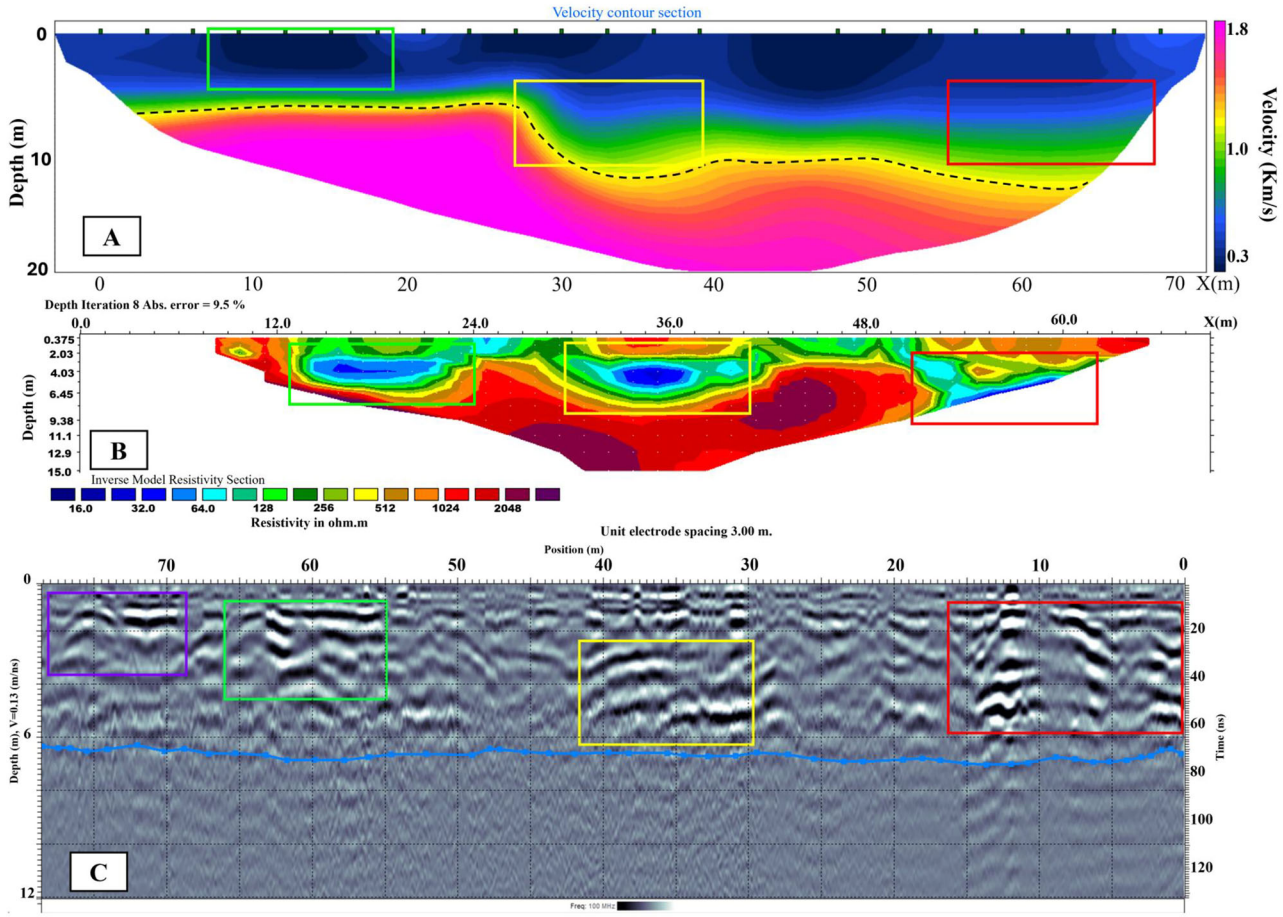


Fig. 9 | Joint interpretation of geophysical profiles. Joint interpretation for three profiles, one for each method, SP-2, RP-2, and GP-3, presented as **A**, **B**, and **C**, respectively. Marked four main groups of anomalous bodies represented by different colours.

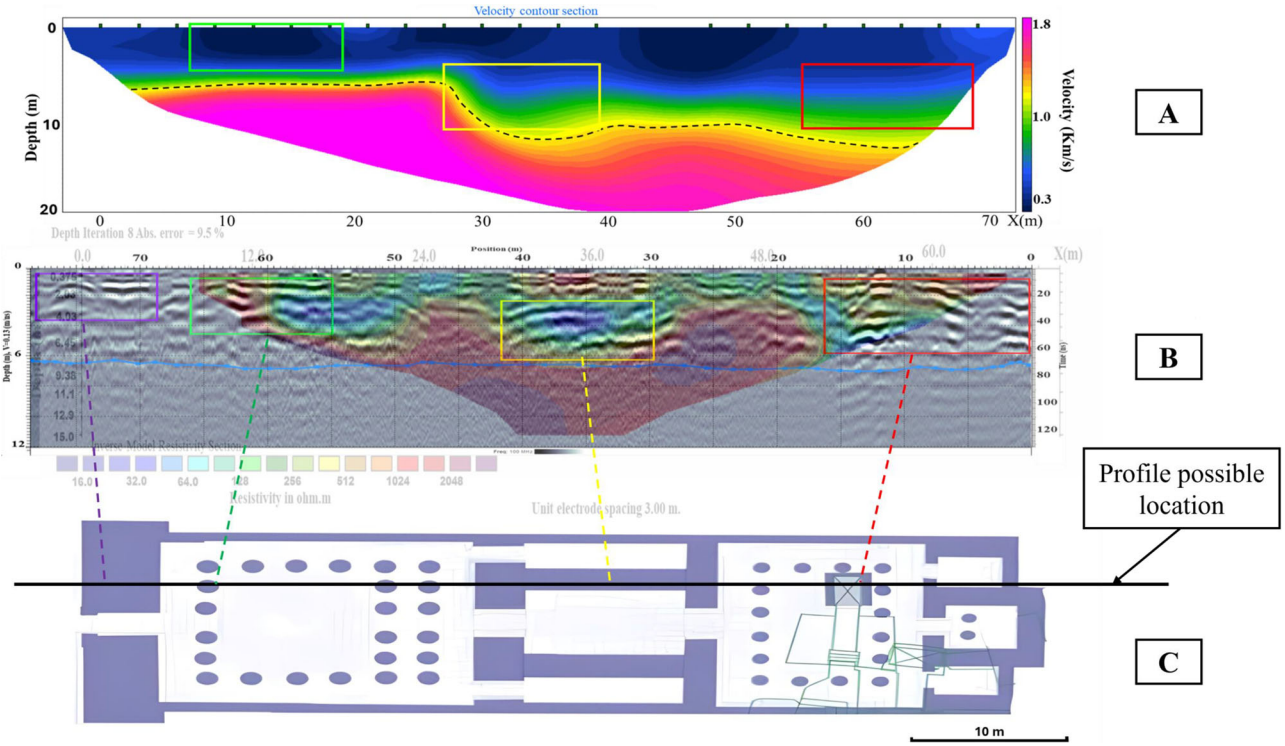


Fig. 10 | Joint interpretation of geophysical profiles and tomb design. A and **B** Joint interpretation for the three techniques SRT profile underlying by layering transparent ERT and GPR sections, **C** Geometrical sketch showing the design of an old, discovered tomb in a nearby study area, adapted from Nico Staring (2023), licensed under a Creative Commons Attribution License (CC BY-NC-ND 4.0), and used by the license terms.

boundary represented by a blue line. Four main anomalous bodies (A1 to A4) were identified, each displaying different radar signatures suggesting large voids, walls, or burial wells (Fig. 6).

The GPR survey consisted of five profiles, starting with GP-1, the closest to the exposed Ptahmose Tomb (Fig. 6a). The first anomalous body (A-1), marked by a purple rectangle, was not detected in GP-1 but appeared in all subsequent profiles. This anomalous body could represent a series of walls and smaller voids, possibly indicating smaller chambers. The second anomalous body (A-2), shown in green, is a distorted signature that may correspond to a collapsed chamber in the area. The third anomalous body (A-3), marked by a yellow rectangle, is a wide, flat feature that might represent the ceiling of a large hall at a depth of 2.5 to 4 metres. The final set of anomalous structures (A-4), indicated by red rectangles, exhibits hyperbolic shapes, which likely correspond to large voids at depths ranging from 0.5 to 4 metres. All these interpretations according to the geometrical overview of the surrounding tombs, which consider the main architectural designs of this historical era.

The GPR profiles were combined (GP-1 to GP-5), providing more information about the detected anomalous bodies' continuity, size, and spatial orientation, which significantly enhances our understanding of the subsurface features and their archaeological implications. (Fig. 7)

Discussion

The study focuses on integrating shallow geophysical techniques to detect subsurface archaeological remains. Given the importance of the Saqqara necropolis, the site has been of interest for many years. The National Museums of Scotland, followed by the Glasgow National Museum, conducted the SGSP under the leadership of Ian Mathieson[10]. Our study area was included in this earlier survey and identified as a promising location for future excavation (Fig. 8). SGSP was a large magnetic survey for mapping subsurface Saqqara, and our study area was delineated as a subsurface anomalous target.

In our investigation, three geophysical methods (SRT, ERT, and GPR) were conducted and their interpretation results were combined to provide a comprehensive understanding of the subsurface structures. Three profiles, one from each method: SP-2, RP-2, and GP-3, were displayed, all representing the same location (Fig. 9).

Table 2 | The recommendations of our findings

	Anomaly Group 1	Anomaly Group 2	Anomaly Group 3	Anomaly Group 4
Marked Colour	purple	green	yellow	red
Probability of Findings	Walls	Room	Large Hall	Shaft and Chamber
Possible Depth	2 m	4 m	2 to 4 m	2 to 6 m

The geophysical survey identified four distinct groups of subsurface anomalous bodies. Three were consistently detected across all profiles, while the fourth was observed exclusively in the GPR data due to the limited coverage of the other methods. The first group, marked by a purple rectangle in the GP-3 profile, consists of hyperbolic reflections, commonly associated with vertical or near-vertical structures. These anomalous bodies are interpreted as a series of walls, potentially forming part of a larger architectural layout.

The second group, outlined in green, corresponds to a closed structure approximately 6 metres in length at a depth of 4 metres. Based on its distinct boundaries and internal signal characteristics, which align with features typically associated with underground chambers, this anomalous body is interpreted as a possible room.

The third group, highlighted in yellow, represents a flat, continuous feature extending up to 10 metres at depths of 2 to 4 metres. Given its horizontal orientation and substantial extent, this anomalous body is interpreted as a large hall or open space, consistent with known archaeological structures in the region.

The final anomalous body, marked in red, appears across all profiles at depths of 2 to 6 m as a series of high-intensity signals originating from the

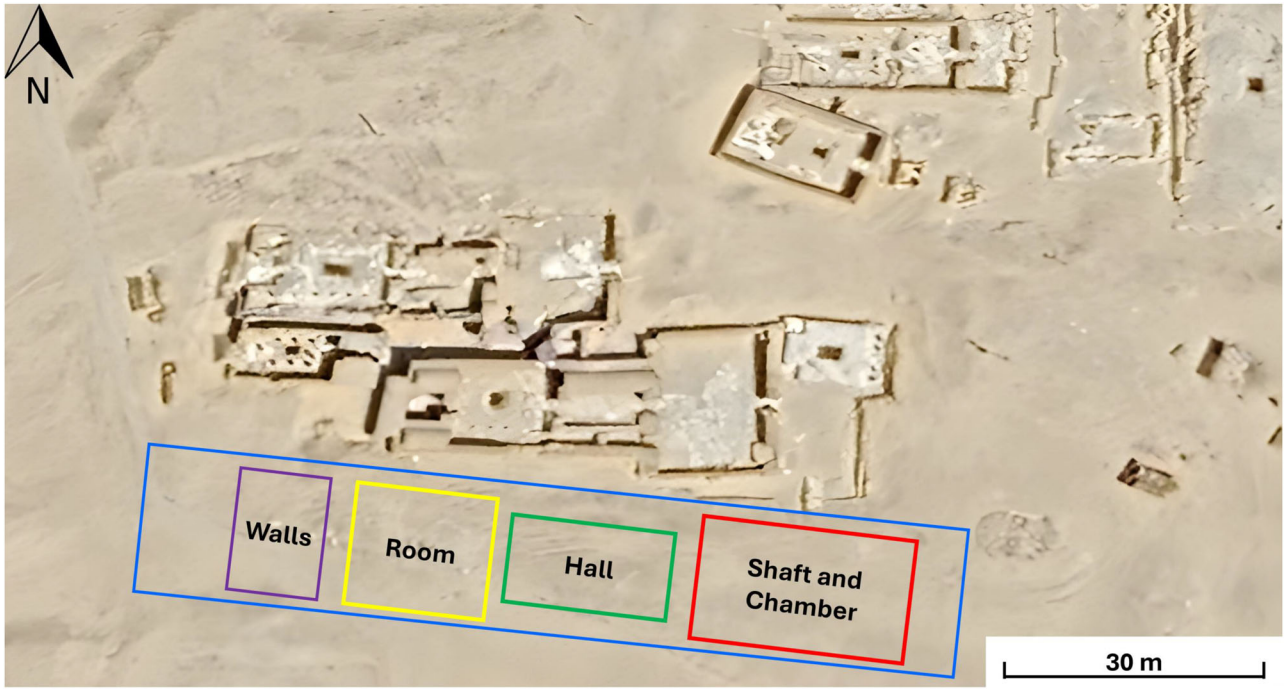


Fig. 11 | Recommended excavation based on geophysical interpretation. The satellite image shows the proposed excavation zones within the study area, each outlined in color. The represent: Walls (purple box), Room(yellow box), Hall (green box), and Shaft and Chamber (red box). (Google Earth pro).

surface and extending downward. These signals are interpreted as a vertical shaft leading to a sizeable subsurface chamber, possibly a tomb or storage area. The interpretation is supported by the source depth and geometry, which are characteristic of shaft-based burial structures commonly found in the area.

These interpretations are grounded in the archaeological knowledge of the region and are further validated by comparisons with the architectural design of nearby tombs, as illustrated in Fig. 10. The close alignment between our geophysical findings and the layout of these known tombs strengthens the reliability of our results. The survey provides valuable insights into the subsurface architecture, offering strong evidence of significant archaeological structures within the study area. These findings deepen our understanding of the site's historical significance and serve as a crucial guide for future excavation strategies, ensuring a more focused and informed exploration of the area.

Based on the results of the integrated geophysical survey and historical knowledge, we recommend initiating excavation efforts at the following locations, which have been identified as high-priority targets as shown in Table 2.

These recommendations spotlight sources that exhibit strong geophysical signatures consistent with human-made structures. By starting excavations at these locations, as shown in Fig. 11, the study can validate the geophysical interpretations and uncover new archaeological evidence, contributing significantly to the understanding of the site's historical and cultural context.

Future work will focus on integrating advanced 3D geophysical modelling to enhance the visualization and interpretation of subsurface features. Expanding the survey area and adopting higher-resolution geophysical tools like multi-frequency GPR will improve data accuracy and depth penetration. Collaboration with archaeologists and historians will ensure interpretations align with established knowledge while contributing new insights. The interpreted anomalous structures are compared to the geometrical sketch of a nearby discovered tomb to validate the final interpretation (Fig. 10C), and it will guide systematic excavations and support the preservation of the Saqqara necropolis for future generations.

The integration of the results from SRT, ERT, and GPR data interpretation has yielded significant insights into the intricate subsurface features of the Saqqara necropolis. This combination of methods reveals several anomalous structures that likely represent ancient, human-made structures interconnected with burial chambers, tombs, and other constructions buried between 2 and 4 metres below the surface. These findings resonate with historical accounts of the site and provide a window into the complex funerary architecture of ancient Egypt, highlighting the time's advanced construction techniques and burial practices.

Beyond identifying individual structures, these findings offer a broader understanding of Saqqara's profound cultural and historical significance. The application of high-resolution, non-invasive geophysical surveys has allowed us to examine the site in remarkable detail, contributing to a more nuanced appreciation of its archaeological complexity. This study underscores the essential role of sophisticated, minimally invasive methods in safeguarding sites rich in heritage, enabling us to access critical information while preserving their integrity.

Our research provides a strong foundation for future excavations and informs and enhances conservation efforts at Saqqara. By strategically guiding these initiatives, we contribute directly to preserving Egypt's invaluable cultural heritage. Moving forward, a collaborative, interdisciplinary approach alongside the continued use of advanced geophysical techniques will be key to uncovering Saqqara's remaining mysteries. This careful and respectful approach will ensure that the legacy of ancient Egyptian civilization remains accessible to future generations, deepening our collective understanding and appreciation of this extraordinary historical landscape.

Data availability

The data supporting the findings of this study are available upon reasonable request from the corresponding author.

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Competing interests

The authors declare no competing interests.

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