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Three-dimensional modelling of a pre-Aksumite settlement at the archaeological site of Seglamen, Aksum, northern Ethiopia using integrated geophysical techniques

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Abstract

This geophysical study is part of a multidisciplinary archaeological research project designed to provide the framework for the reconstruction of the cultural and environmental history of the region to the southwest of Aksum and for the production of a detailed archaeological map for the cultural heritage management of central Tigray. Seglamen, near Aksum in north Ethiopia, an area of about 70 000 m^2, is dated from the early to mid-first millennium BCE and has been detected and excavated since 2010 by the Italian Archaeological Expedition of the University of Naples "L'Orientale". An objective of this study was to develop a geophysical model that defines the archaeological context of a multilayered archaeological site. In doing so, it was also aimed at guiding future excavations operated by archaeologists on the site, thereby assess the geophysical techniques that work well in this area and make recommendations to several archaeological research projects that have been operating at and around Aksum, with similar archaeological context. Magnetic and electrical resistivity tomography (ERT) techniques were employed. The magnetic reconnaissance survey carried out at 2 m station spacing and 5 m line spacing covering the area and has outlined for further detailed investigation localized anomalies for the ERT. Detailed ERT survey was conducted on a rectangular grid of 21.75 × 44.25 m^2 with 0.75 m unit electrode spacing and 0.75 m line spacing. It has yielded two-dimensional (2D) and three-dimensional (3D) electrical resistivity sections of the surveyed area. From combined interpretation of the magnetic and electrical imaging survey data, it was possible to delineate localized anomalous zones that could be associated with the existence of subsurface features of archeological interest. Interpreted stone-based walls were validated through test excavations that revealed well preserved and collapsed walls. These cultural structures are sometimes located at depths of about 20 cm so there is a high possibility of destruction by farming activities of local farmers; ultimately, we would urge conservation work in this area.

KEYWORDS

3D modelling, electrical resistivity tomography, magnetic anomalies, multilayered, pre-Aksumite settlement, Seglamen

1 | INTRODUCTION

Operation in an archaeological site often has to be non-invasive. Geophysical investigations, amongst their many other advantages, provide excellent means to fulfil this stringent criterion. A number of geophysical techniques have found wide applications in archaeological site prospection of which the most important are magnetic, ground-penetrating radar (GPR) and electrical resistivity methods. With the advent of improved instrumentation and data interpretation software, it has now become possible to map, in three-dimensions, complex potential archeological sites and guide field excavations.

Two methods that have been employed in the current survey include the electrical resistivity imaging and the total field magnetic survey techniques (Batayneh, 2011; Drahor, 2006; Forte, Pipan, & Sugan, 2003). Electrical resistivity imaging/tomography (ERT) is a non-invasive technique increasingly being employed in archaeological prospecting, where detailed knowledge of the subsurface is sought (Forte et al., 2003; Papadopoulos, Tsourlos, Tsokas, & Sarris, 2006; Urbini, Cafarella, Marchetti, Chiarucci, & Bonini, 2007). The technique depends on the resistivity contrast between the buried archaeological structures and the covering soil, which play an important role in the mapping of buried anthropogenic features like tombs, and masonary. In building up a two-dimensional (2D) pseudodepth section of the apparent resistivity and depth sections of inverted resistivity, one needs data collected along a measuring line by different electrode configurations. Similar duplicate and, most preferably, gridded data acquisition procedures can also be achieved for three-dimensional (3D) surveys. To image the subsurface, electrical resistivity data can be evaluated by tomographic inversion methods that result in true models of the subsurface in two and/or three dimensions.

Recently, modern ERT systems that permit the collection of very large data sets providing coverage of relatively larger areas at high data density have become available (Papadopoulos et al., 2006). Yet, resistivity data still tend to be collected using the standard electrode arrangements, such as the Wenner, Schlumberger or dipole–dipole arrays. These arrays are often a good choice, as they are well understood in terms of their depths of investigation, lateral and vertical resolutions and signal-to-noise ratios (Barker, 1989; Dahlin & Zhou, 2004; Martorana, Fiandaca, Casas Ponsati, & Cosentino, 2009).

Optimized electrode configurations are also important in ERT surveys to make quick measurements as they allow the collection of a limited number of measurements without compromising the tomography image (Stummer, Maurer, & Green, 2004; Wilkinson, Meldrum, Chambers, Kuras, & Ogilvy, 2006). However, the ERT (3D) survey remains cumbersome, as an array of electrodes has to be moved for large areal coverage even with those optimized sets of electrode configurations. Therefore, the ERT method has to be integrated with other geophysical methods for a methodological approach designed to define areas of maximum interest where ERT data collection should be planned.

The magnetic method, however, is the most frequently used geophysical tool for archaeological prospection because of its ease in field operation, the large speed it provides in data collections and its resolution in mapping large areas (Batayneh, 2011; Shaaban, El-qady, Khozaym, Al-emam, & Ghazala, 2014). This method has been used to map buried stone foundations and soil features such as ditches, pits, trenches, etc. as this may maintain contact or interface between domains of different susceptibility and to outline the locations of strongly magnetized structures such as forges, kilns, hearths, and campfire sites as these acquire stronger magnetization from burning (Kaufmann, Ullrich, & Hoelzmann, 2015; Leucci et al., 2015; Tsokas & Hansen, 2000). Recent advance in technology has allowed the acquisition of large databases and more precise evaluation of field data (Ansari & Alamdar, 2009; Li & Oldenburg, 1996).

In this work, the magnetic method was used to define the macro-area; outline and generally localize anomalies of potential archaeological interest from a very large archaeological site at Seglamen. The ERT, in this case becomes an efficient option if used for further detailed investigation of these outlined anomalies of potential archaeological importance.

Geophysical study of the site is currently in progress as part of an archaeological research project of the Italian Archaeological Expedition of the University of Naples “L'Orientale” (UNO) designed to provide the framework for the reconstruction of the cultural and environmental history of the region to the southwest of Aksum that covers an area of 100 km^2 and the production of a detailed archaeological map of this region for the cultural heritage management of central Tigray.

The objective of geophysics in this work is to develop a geophysical model that defines the archaeological context of a multilayered archaeological site of Seglamen in Aksum area, northern Ethiopia. In doing so, it is also aimed at guiding future excavations by archaeologists operating on the site, thereby assessing the geophysical techniques that work well in this area. Several archaeological research projects have been operating at and around Aksum and few, if any of them, employed geophysical techniques. The work is, therefore, pioneering in the area and may initiate research projects to consider these geophysical techniques at sites with similar archaeological context.

2 | THE SEGLAMEN ARCHAEOLOGICAL SITE: LOCATION, MORPHOLOGY AND GEOLOGY

The greater area of Aksum (Central Zone, Tigray) is a well-known region of archaeological interest in Ethiopia and has been the subject of much study and research in relation to the emergence and decline of the Aksumite civilization (Phillipson, 2012). About 12 km to the southwest of Aksum's city-centre is the modern village of Seglamen where a relevant site dated from the early to mid-first millennium BCE has been detected and excavated since 2010 by the Italian Archaeological Expedition of the University of Naples “L'Orientale”, in collaboration with Aksum University (Fattovich, 2012; Sernicola, Makonnen, & Phillipson, 2013; Sernicola & Phillipson, 2014; Sernicola, Capra, Gaudiello, Kribus, & Phillipson, 2015; Sernicola et al., 2016). The site is bounded by the Mai Negus/Haselo river gorge on the north and northeast, the Ferasit and Grat Gabara hills on the southwest, Teenti hill on the west and Kesaad Addi Kerni hill on the northeast (Figure 1). It extends over an area of about 70 000 m^2 at the edge of the western cliff of the Negus river gorge, and encompasses the areas of Amda Tsion and Mogareb, in the eastern sector of the village,

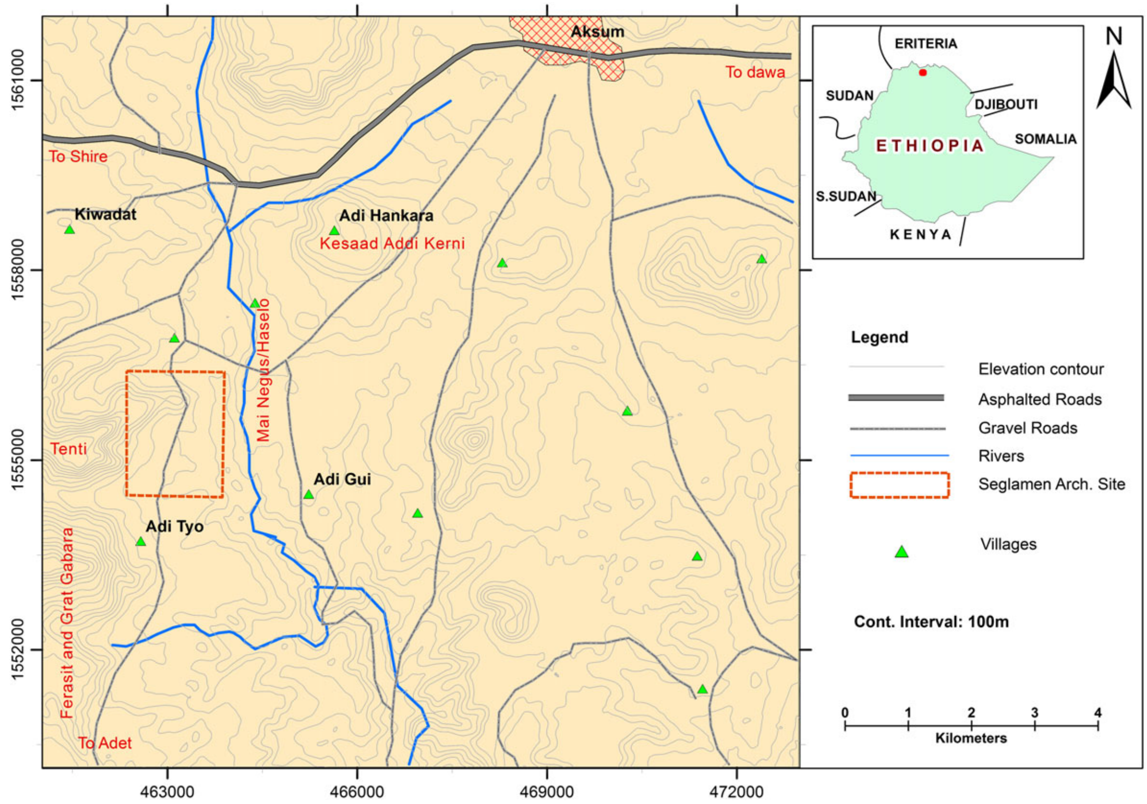

FIGURE 1 Location map of the Seglamen archaeological site, Aksum, North Ethiopia [Colour figure can be viewed at wileyonlinelibrary.com]

where concentrations of artefacts and architectural elements are still visible on the surface.

Archaeological research at Seglamen is part of a broader project launched in 2010. Traces of the possible occurrence of an archaeological site in the area dating back to the first half of the first millennium BCE emerged in the early 1970s, when a royal inscription in monumental South-Arabic, attributable to the so-called "pre-Aksumite" period and commemorating the re-erection or restoration of a temple dedicated to the god *hbs*, was found by local farmers at Amda Tsion, in the southeastern sector of the modern village (Bernand, Drewes, & Schneider, 1991; Schneider, 1976). Preliminary excavations aimed at detecting archaeological remains in the area were carried out in 1974 by the University of Rome "La Sapienza", under the direction of Lanfranco Ricci (Ricci & Fattovich, 1987). These brought to light a large post-Aksumite (c. CE 800/850–1300) rural house, apparently built on earlier foundations. The actual location of the pre-Aksumite settlement was found/excavated in 2006, during the systematic survey of Aksum and its vicinities conducted in the framework of the World Bank Ethiopian Cultural Heritage Project (Fattovich & Hagos, 2006; also reported at http://opar.unior.it/1294/1/IEAks_UNO_2010_final_report), and was confirmed in 2009, after a visit to the site by members of the UNO expedition and representatives from Aksum University and the Bureau of Culture and Tourism, Central Zone, Aksum.

Since 2010 to date, seven field seasons of archaeological investigations have been conducted at the site of Seglamen. These allowed the identification of two different areas within the site: the settlements and the cemetery.

Excavations conducted in the area of the settlement exposed the remains of three major architectural phases, all ascribable to the pre-Aksumite period on the basis of ceramics and other materials, as well as radiocarbon dating (Fattovich, 2012; Sernicola et al., 2013; Sernicola & Phillipson, 2014). Excavations at the cemetery brought to light shaft tombs roughly rectangular or circular in plan, some of them associated with sandstone monoliths, as well as small votive deposits.

Based on the geological mapping conducted at regional scale (1:250 000) the area around Aksum is composed of two main lithologic units of Tertiary age namely the Koyetsa volcanics and the Adwa trachyte formation (Figure 2; Ethiopian Institute of Geological Surveys, 1996). The Koyetsa volcanics form a gently undulating plateau surface that is intruded by numerous volcanic plugs belonging to the Adwa trachyte formation (Schmid, Koch, Diblasi, & Hagos, 2008). Overlaid by the flood basalt is the Adigrat sandstone: reddish, laminated sandstone, conglomerate and minor Paleozoic tillite exposed at the eastern part of the Aksum area along major river gorges.

Geomorphologically, the Tertiary basalts form a distinctive terraced topography with a succession of flat surfaces and steep steps. Quaternary deposits consisting of alluvium, colluvium and tuff cover are found along major river valleys, in depressions, and along the lower slopes of volcanic domes (Schmid et al., 2008). The lithologic and topographic variation reflects the different types of soils that are found within the area. Generally speaking, the study area is a flat terrain in the Koyetsa volcanic where the soil contains dark grey silty clay.

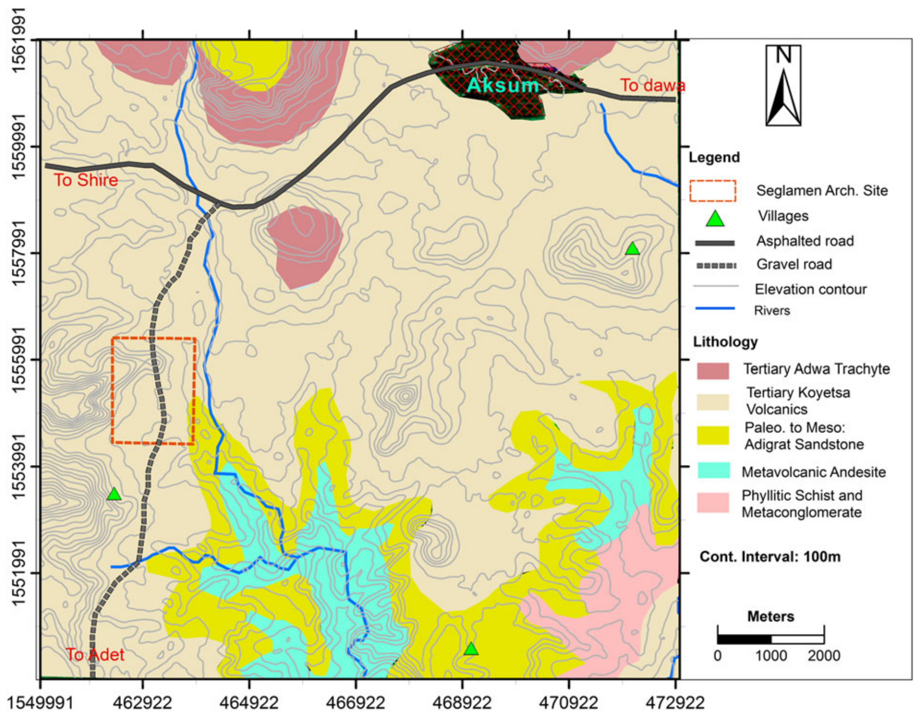

FIGURE 2 Geological map of Aksum area with the Seglamen archaeological site shown with a rectangular marking (modified from geological survey of Ethiopia, Aksum sheet, 1996) [Colour figure can be viewed at wileyonlinelibrary.com]

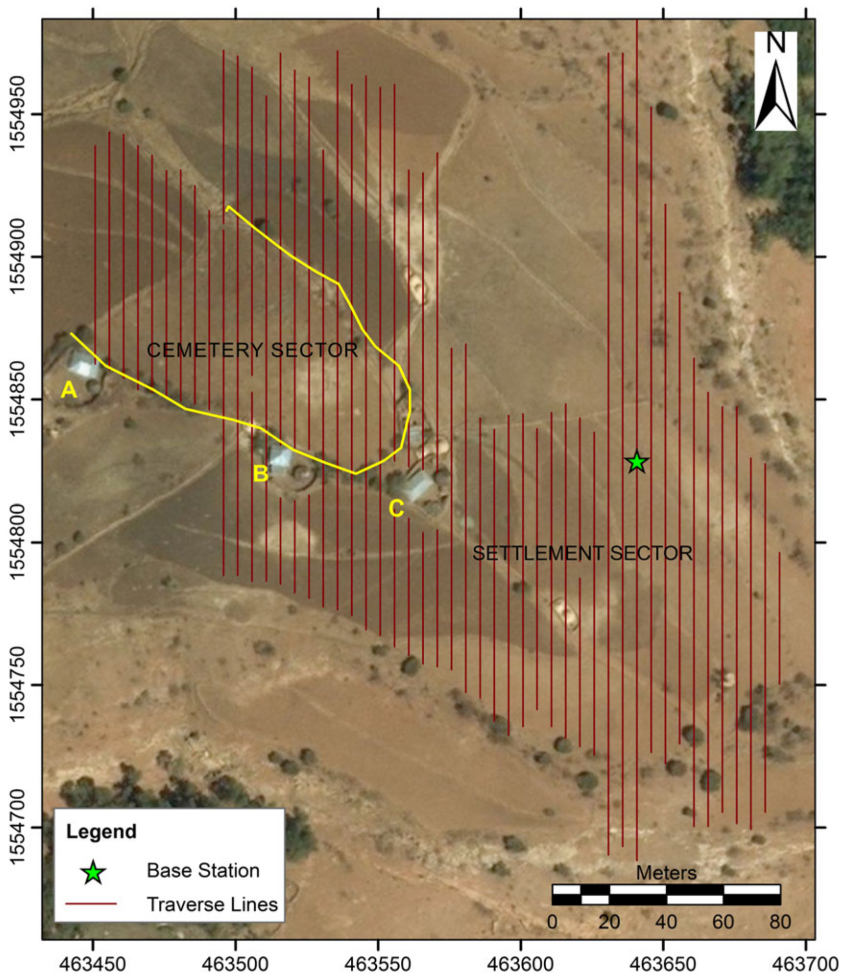

FIGURE 3 Magnetic survey area and traverse lines, showing lines spaced at 5 m interval and the magnetic survey base station [Colour figure can be viewed at wileyonlinelibrary.com]

3 | METHODS AND INSTRUMENTATION

The geophysical methods employed in the current survey include magnetic and ERT. A combination of this suite of methods is believed to provide adequate information to characterize the Seglamen archeological site.

The reconnaissance magnetic survey at Seglamen was considered only as a first step analysis to define areas of maximum archaeological potential out of a large archaeological site (an area of more than 70 000 m^2), partially investigated by archaeologists in previous excavations. This survey was planned to be followed by more localized, detailed high resolution ERT surveys designed to achieve the goal of complete mapping of the selected areas and perhaps localize a few isolated and distinctive features.

Field procedures for the magnetic prospection method have been refined considerably in the last two decades. Currently, the use of magnetic gradiometer and microcomputer-controlled automatic data collection systems have enabled low-noise and high-productivity surveys (Clark, 2003; Gaffney, Gater, Linford, Gaffney, & White, 2000; Kaufmann et al., 2015; Shaaban et al., 2014). However, the available model MP2 proton precession magnetometer (Scintrex) was used to acquire the total field magnetic data with the aim of outlining the spatial distribution of intra-site magnetic anomalies of potential archaeological significance.

Profile lines trending north–south (N–S) were made in order to transect possible foundation walls based on a priori information from active excavation units during the time of the geophysical surveys (Figure 3). There is a general trend of the masonry work observed at the active excavation units (having at some areas lengths greater than 6 m) striking in a northwest–southeast direction. A base station was occupied with the same roving magnetometer every 20 to 30 min for the sake of correcting the diurnal variation of the magnetic field. Total field magnetic data that covered the whole of the archaeological site (study area) were collected along 49 profile lines at 5 m line spacing and 2 m measuring point spacing.

The design of the ERT survey, however, was based on the results of the reconnaissance magnetic survey and observations of different previously open excavation units at two sectors of the site, the cemetery and the settlement areas. These excavations identified tombs (graves) and buried remnants of stone-based walls of ancient settlements plans, respectively, as potential archaeological features likely to be encountered. The unearthed walls are mainly made from Paleo to Meso sandstones (Adigrat sandstones) which are expected to show a strong positive magnetic anomaly as sandstones have higher magnetic susceptibility compared to the background clay soil surrounding the walls. Electrical resistivity of sandstones range 200 to 8000 Ω m depending on their grain size, degree of fracturing, moisture content and degree of saturation. Walls are expected to give much lower values of electrical resistivity because of the secondary filling material (clay soil mortar) but higher when contrasted to the soil surrounding them.

Three-dimensional ERT modelling studies point out that the dipole–dipole array generates images that are close to the models used (Berge & Drahor, 2011). Additionally, this array was chosen to perform the survey as it is very sensitive to lateral changes in resistivity (very good horizontal resolution), has a good lateral coverage, and low electromagnetic coupling between the current and potential circuits.

The SYSCAL R1 plus Switch unit with 72 electrodes (Iris Instruments) was used for acquisition of ERT data in all grids. Eight grids, G1A, G1B, G1C, G2A, G2B, G3A, G3B, and G4A (Figure 4) of different sizes were laid on intra-site areas of maximum potential archaeological interest. These areas of interest were outlined by the magnetic survey for further detailed investigation by the ERT

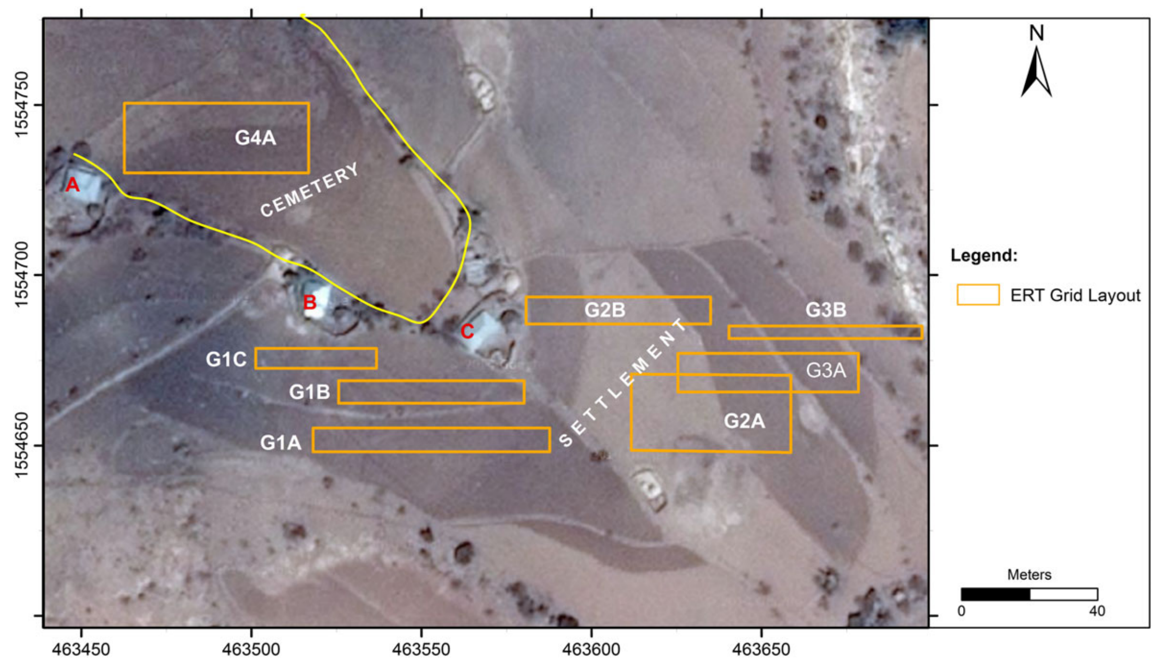

FIGURE 4 Electrical resistivity tomography (ERT) survey grid layouts; G4A is on the cemetery site while the other grids are located on the settlement areas and ERT results of G2A is introduced in this work [Colour figure can be viewed at wileyonlinelibrary.com]

technique. The results for grid G2A located on the settlement area are discussed in this article.

Figure 4 shows the layout of the various ERT survey grids. Grid G2A, whose results are discussed in detail in this work, is 53.25 m × 21.75 m in size and is constituted by 30 parallel transects. All transects were traversed west to east with 0.75 m spacing between them. Unit electrode spacing was 0.75 m for all transects and six depth levels were adopted.

4 | DATA PRESENTATION AND RESULTS

The raw total magnetic field observed, as expected, is disturbed with noise. These raw data were however subjected to a number of data correction and enhancement schemes using the Oasis montaj (Geosoft) software. The residual magnetic data were first corrected for diurnal variations and spikes were removed for further enhancement and improved presentation. Zero Mean Traverse (ZMT) was applied to remove the strips and the result is depicted in Figure 5. Clear magnetic anomalies referable to buried, potentially cultural features are evident on the map in the cemetery and residential sectors of the site (Sector 1 and Sector 2, respectively). The magnetic anomalies marked with red rectangles in Sector 2 and black ellipses in Sector 1, showing higher magnetic response, draw more interest as the potential archaeological features. They are areas where the ERT survey was planned and subsequently conducted. The blue rectangle in Sector 2 shows a magnetic anomaly corresponding to a previously refilled excavation which is compared to the rest of the anomalies to speculate those targets of potential archaeological interest (Sernicola et al., 2013). The white rectangle in Sector 2 highlights the grid G2A Magnetic measurements were affected by modern houses (Figure 5, A–C). Therefore, the map is not definitive close to the houses as magnetic anomalies of subsurface origin were hampered by anomalies linked to iron materials of the houses.

The ERT survey grids were constituted by dense parallel transects that are adequate to reconstruct buried structures by combining them in a 3D scheme (Papadopoulos et al., 2006). The 2D and 3D inversion models were developed from the acquired ERT data using RES2DINV and RES3DINV inversion programs.

The inversion routines are based on the smoothness-constrained least-squares method and the forward resistivity calculations were executed by applying an iterative algorithm based on a finite-difference method (Loke & Dahlin, 2002; Loke & Barker, 1996a, 1996b). The inversion procedure uses a starting model that divides the subsurface into a number of small rectangular cells/blocks and attempts to determine the resistivity values of the cells/blocks so as to minimize the difference between the calculated and the observed apparent resistivity values. The goodness-of-fit is expressed in terms of the root mean square (RMS) error. The width of the starting model cell for the forward modelling subroutine is set to be half the unit electrode spacing due to large resistivity variation near the ground surface and a RMS error less than 4% was attained in six iterations for each 2D inversion model. An RMS value of 2.70% was achieved in the same number of iterations in the 3D inversion procedure. Graphic presentations of the inversion results are output from the Surfer software (Golden Software).

Consecutive 2D inversion geoelectric sections that possibly define archaeological features were clustered to produce quasi-3D models (Berge & Drahor, 2011; Papadopoulos, Tsourlos, Tsokas, & Sarris, 2007) (Figures 6–8). The 2D apparent resistivity data were collated by the RES2DINV software and processed in a 3D inversion-scheme to develop a semi-fully 3D ERT model (Figure 9).

These results, generally, show that potential archaeological activities are confined in the roughly 1.5–2.5 m thick soil overlying the

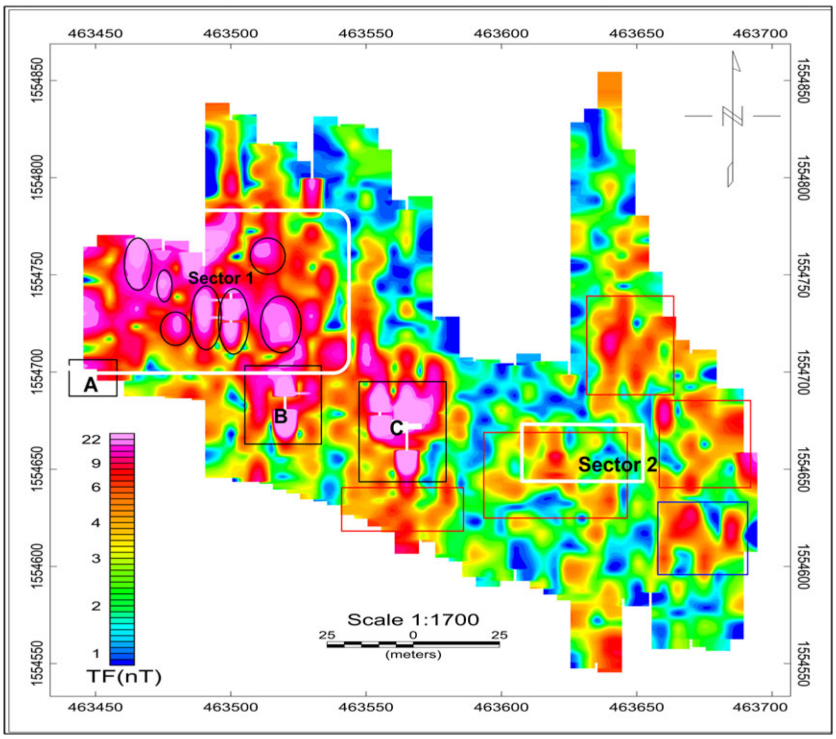

FIGURE 5 Residual magnetic field anomalies outlined from the enhanced/corrected magnetic field data [Colour figure can be viewed at wileyonlinelibrary.com]

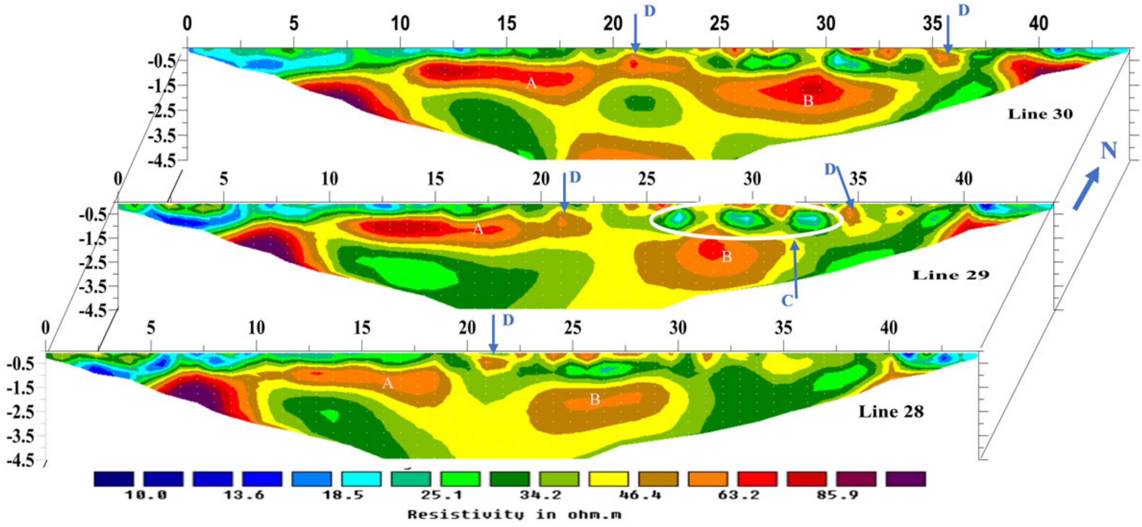

FIGURE 6 Cluster of consecutive two-dimensional (2D) inversion results showing lines 28, 29, and 30 [Colour figure can be viewed at wileyonlinelibrary.com]

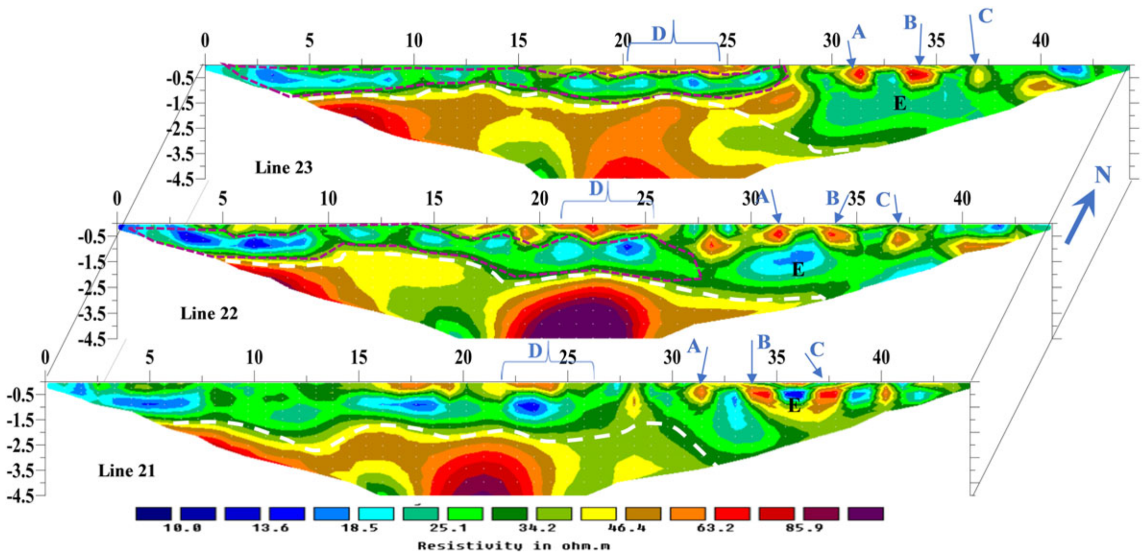

FIGURE 7 Cluster of consecutive two-dimensional (2D) inversion results showing lines 21, 22, and 23 [Colour figure can be viewed at wileyonlinelibrary.com]

bedrock. Field observation of rock samples along river cuts bordering the settlement suggested that the Adigrat sandstone is the shallowest rock layer and may correspond to the bedrock. The stone-based walls are described by higher resistivity as east–west (E–W) oriented and vertical cross-sections. The broad, mostly higher resistivity anomalies from the deeper horizon correspond to the bedrock.

Label A in Figure 6 shows a roughly 7 m long and 1.5 m wide higher resistivity structure which probably is a wall in an E–W orientation. This thickness is comparable to that of the outer walls determined to be 1.20 m from previous excavations. The feature labelled B may also be a stone-based structure, poorly resolved because of its depth. Label D shows transects of walls trending N–S by lines 28, 29, and 30. The low resistivity patches labelled by C could have resulted from the living floors dissected by the higher resistivity walls exhibiting (demonstrating) the pronounced lateral resolution capability of the method at shallower depth. The anomalies interpreted as stone-based features sit at different depths, in some cases overlying one another, defining the site as a multilayered archaeological site in agreement with previous excavations.

High resistivity anomalies shown by A, B, and C in Figure 7 are similarly interpreted as wall cross-sections transected by lines 21, 22 and 23 and anomaly E shows room floors.

The top thin high resistivity layer in Figures 6–8 might have resulted from the loose dry soil of the ploughed land. But ground truthing by opening a 2 × 2 m^2 pit at D in Figure 7 verified a collapsed and not well-preserved wall (Figure 10(a)). Underlying this layer is a *c.*1 m thick, laterally extended, conductive horizon (bounded by a pink dashed line in Figures 7 and 8) which could possibly be soil as the low laying adjacent

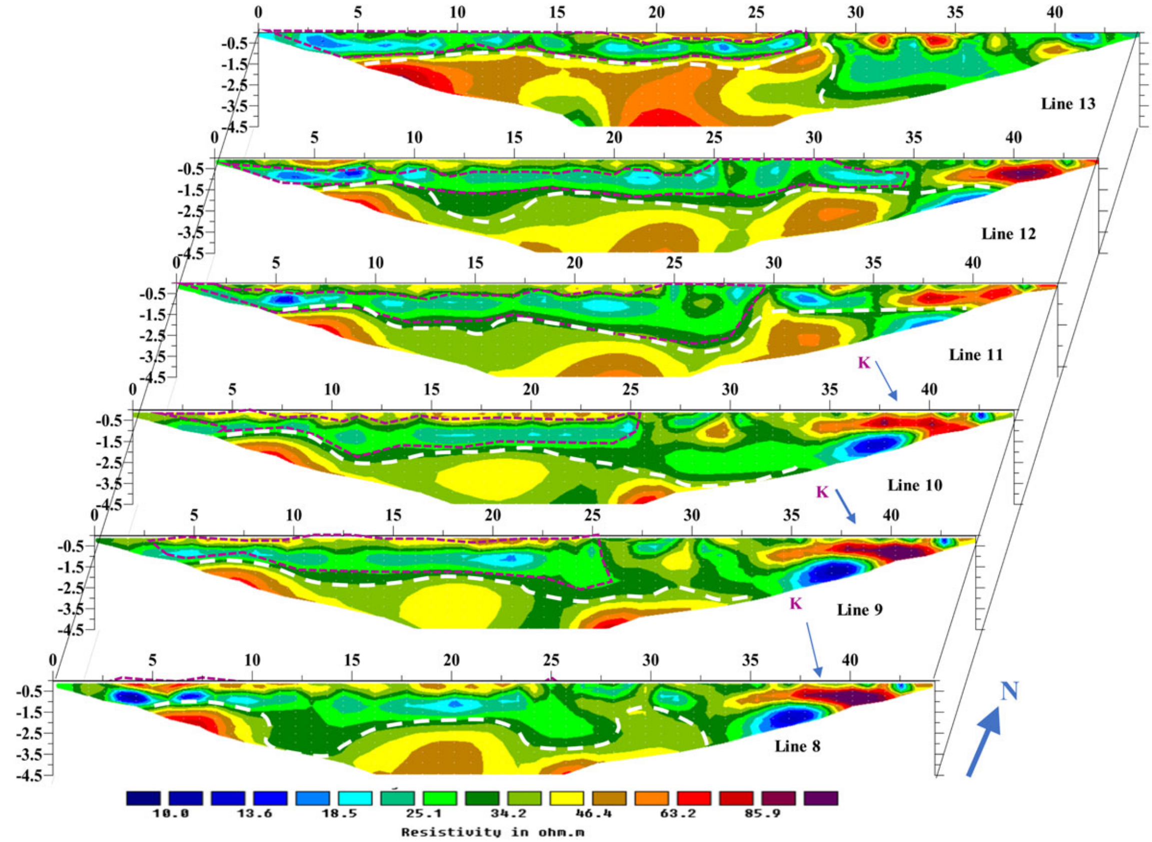

FIGURE 8 Cluster of consecutive two-dimensional (2D) inversion results showing lines 8–13 [Colour figure can be viewed at wileyonlinelibrary.com]

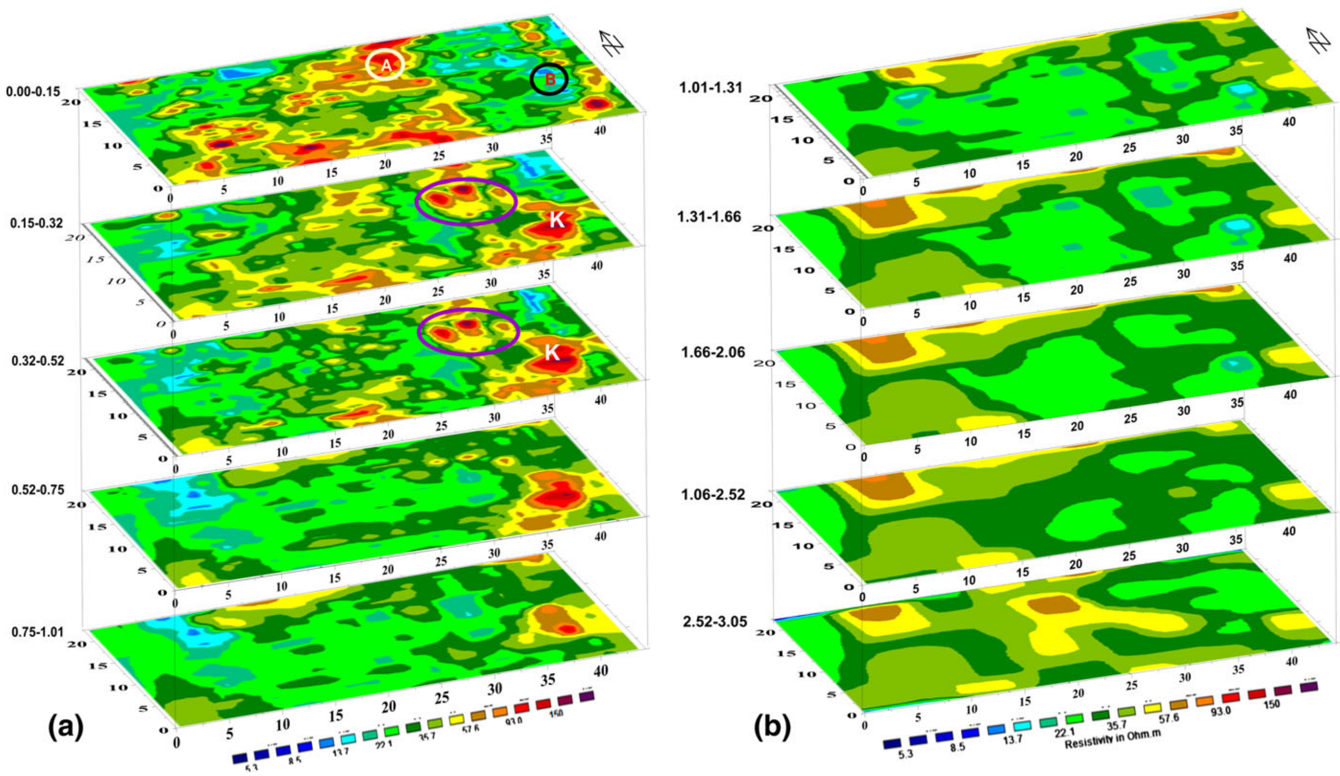

FIGURE 9 The semi-fully three-dimensional (3D) inversion model, depth is limited to 3.05 m [Colour figure can be viewed at wileyonlinelibrary.com]

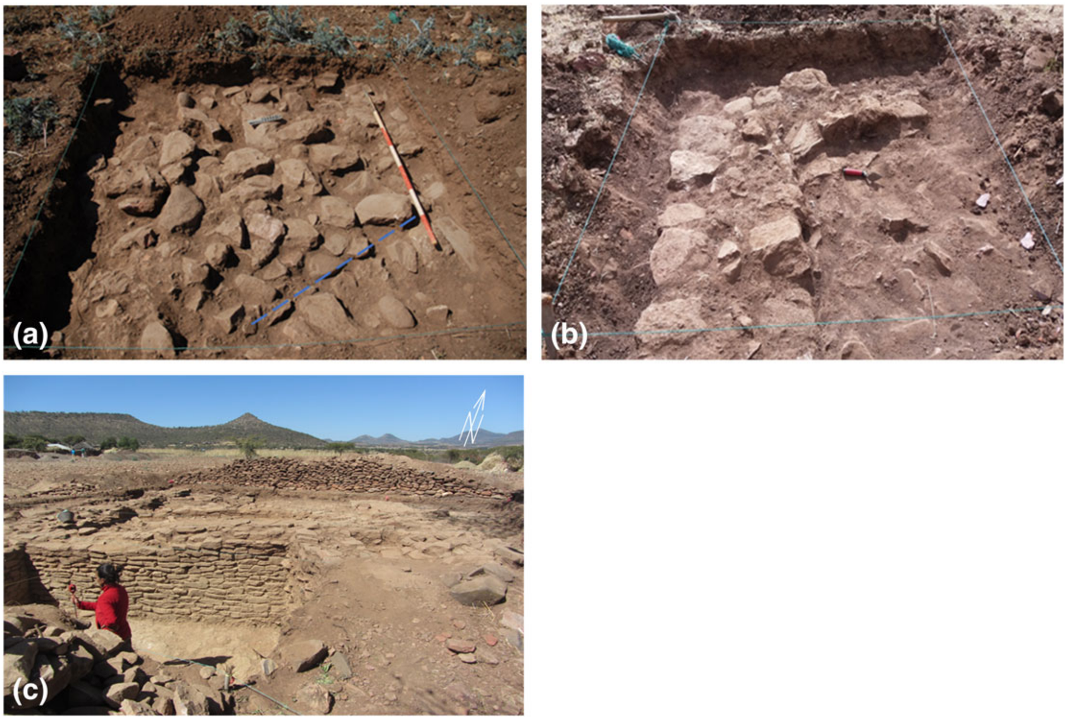

FIGURE 10 Photographs (a) and (b) show validation of the interpreted electrical resistivity tomography (ERT) anomaly through excavations of 2 × 2 m^2 pits and (c) shows previous backfilled excavation corelated to the magnetic anomaly shown in Figure 5 and the results of the ERT survey [Colour figure can be viewed at wileyonlinelibrary.com]

bedrock is likely impervious so that the soil keeps moist. A 2 × 2 m^2 pit was opened to verify the anomaly indicated by the label K in Figure 8 and it defines a well-preserved stone-based wall (Figure 10(b)).

Figure 9 depicts the semi-fully 3D geoelectric model. The depth is limited to 3.05 m by the RES3DINV program, having learned from the 2D inversion models that the archaeological activity area is confined to less than this depth. This also cures the problem of insufficient RAM memory of the computer to carry out the inversion procedure. Label A locates the 2 × 2 m^2 pit that was open to verify the high resistivity anomaly at this location. This anomaly is also shown as D in Figure 7. The pit revealed a collapsed and not well-preserved wall as shown in Figure 10(a). In Figure 10(a) the structures are not exhaustedly exposed indicating that they have a lateral extent wider than the pit. Label B shows another 2 × 2 m^2 pit opened with the intention of verifying the higher resistivity anomaly shown as K in Figures 8 and 9. But, as shown in Figure 10(b), well-defined masonry showed up at a depth of approximately 20 cm. Figure 10(b) may not ground truth K but may indicate the shallowest part of K. Figure 10(c) shows previous back-filled excavation. The walls excavated in Figure 10(c) had depths comparable to the anomalies A and B in Figure 6 and K in Figures 8 and 9.

The purple ellipses in Figure 9 show the anomalies indicated as A, B, and C in Figure 7. It can be seen from Figures 7 and 9 that the 2D sections in Figure 7 have good resolution that clearly defines a regular block shape of a wall cross-section and the anomalies in the purple ellipses in Figure 9 demonstrated A, B, and C are horizontally continuous in a N–S orientation. The linear higher resistivity anomaly features in Figure 9 may generally be interpreted as stone-based walls or collapsed walls and suggest locations of future archaeological excavations.

5 | CONCLUSIONS

The site of Seglamen is ploughed land cultivated by local farmers. This is disturbing the near surface and risking cultural structures which are sometimes located at depths of about 20 cm ultimately urging the need for conservation work.

On top of its speed and ease in field operation, the magnetic reconnaissance survey was able to delineate gross unresolved anomalous targets (sandstone-based walls and collapsed walls) of potential archaeological interest for further investigation. These targets responded so well to the magnetic survey that the technique, deployed at smaller station and line spacings, can be a stand-alone solution to similar geophysical/archaeological problems in the area. The result of a gridded imaging data acquired with the dipole–dipole electrode configuration at grid G2A in the settlement sector showed stone-based archaeological features, some of which were checked through test excavations and found to be well preserved and collapsed walls. Further, the resistivity inversion models presented near surface structures with high resolution that decreases with depth. This shows that the ERT survey deployed with the dipole–dipole electrode configuration may not be the most efficient option when the area of investigation is very large and higher target resolution is sought at a deeper horizon. However, the use of optimized electrode configurations that result in higher resolution of the tomography image, focused on methodologically outlined localized targets, justifying the viability of the ERT technique when a study area is as large as the Seglamen site.

The geophysical survey conducted in the archaeological site of Seglamen showed that the geophysical techniques employed offer the possibility to efficiently characterize cultural subsurface structures. There are several archaeological research projects that have been operating in similar archaeological context at and around Aksum and few, if any of them employed geophysical techniques. It is recommended these research projects may consider using these geophysical techniques at sites with a similar archaeological context.

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REFERENCES

Ansari, A. H., & Alamdar, K. (2009). Reduction to the pole of magnetic anomalies using analytic signal. *World Applied Sciences Journal*, *7*(4), 405–409.

Barker, R. D. (1989). Depth of investigation of collinear symmetrical four-electrode arrays. *Geophysics*, *54*(8), 1031–1037.

Batayneh, A. T. (2011). Archaeogeophysics – Archaeological prospection – A mini review. *Journal of King Saud University(Science)*, *23*, 83–89. https://doi.org/10.1016/j.jksus.2010.06.011

Berge, M. A., & Drahor, M. G. (2011). Electrical resistivity tomography investigations of multilayered archaeological settlements: Part I – Modelling. *Archaeological Prospection*, *171*, 159–171. https://doi.org/10.1002/arp414

Bernand, É., Drewes, A. J. & Schneider, R. (1991-2000). *Recueil des inscriptions de l'Éthiopie des périodes pré-axoumite et axoumite. Introduction de Fr. Anfray*, I: *Les documents*; II: *Les Planches*. Paris: Académie des Inscriptions et Belle-Lettres, Diffusion de Boccard 1991; Bernand É., id., III: *Traductions et commentaires*, A: *Les inscriptions greques* 2000.

Clark, A. (2003). *Seeing beneath the soil: Prospecting methods in archaeology*. London, UK: Routledge.

Dahlin, T., & Zhou, B. (2004). A numerical comparison of 2D resistivity imaging with 10 electrode arrays. *Geophysical Prospecting*, *52*, 379–398.

Drahor, M. G. (2006). Integrated geophysical studies in the upper part of Sardis archaeological site, Turkey. *Journal of Applied Geophysics*, *59*, 205–223. https://doi.org/10.1016/j.jappgeo.2005.10.008

Ethiopian Institute of Geological Surveys (1996). *Geological Map of Ethiopia*, *Aksum Sheet*. Addis Ababa, Ethiopia: Ethiopian Institute of Geological Surveys.

Fattovich, R. (2012). The northern horn of Africa in the first millennium BCE: Local traditions and external connections. *Rassegna di Studi Etiopici*, *4*, 1–60.

Fattovich, R., & Hagos, T. (2006). Archaeological survey – report of activity, March–May 2006 and Aksum World Heritage Site Management Plan. Technical report of the archaeological survey conducted in the area of Aksum in the framework of the Ethiopian Cultural Heritage Project – Aksum branch – site inventory and documentation component submitted to HYDEA s.r.l., Florence.

Forte, E., Pipan, M., & Sugan, M. (2003). Integrated geophysical study of archaeological sites in the Aquileia area. Retrieved from http://ceur-ws.org/Vol-806/paper4.pdf

Gaffney, C., Gater, J. A., Linford, P., Gaffney, V. L., & White, R. (2000). Large-scale systematic fluxgate gradiometry at the roman city of Wroxeter. *Archaeological Prospection*, *7*, 81–99. https://doi.org/10.1002/1099-0763(200006)7:2<81::AID-ARP145>3.3.CO;2-Y, http://opar.unior.it/1294/1/IEAks_UNO_2010_final_report

Kaufmann, G., Ullrich, B., & Hoelzmann, P. (2015). Two Iron-age settlement sites in Germany: From field work via numerical modeling towards an improved interpretation. *Archaeological Discovery*, *3*, 1–14.

Leucci, G., Masini, N., Rizzo, E., Capozzoli, L., De Martino, G., De Giorgi, L., … Rizz, E. (2015). Integrated archaeogeophysical approach for the study of a medieval monastic settlement in Basilicata. *Open Archaeology*, *1*, 236–246. https://doi.org/10.1515/opar-2015-0014

Li, Y., & Oldenburg, D. W. (1996). 3-D inversion of magnetic data. *Geophysics*, *61*(2), 394–408.

Loke, M. H., & Barker, R. D. (1996a). Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method 1. *Geophysical Prospecting*, *44*(1), 131–152. https://doi.org/10.1111/j.1365-2478.1996.tb00142.x

Loke, M. H., & Barker, R. D. (1996b). Practical techniques for 3D resistivity surveys and data inversion 1. *Geophysical Prospecting*, *44*(3), 499–523. https://doi.org/10.1111/j.1365-2478.1996.tb00162.x

Loke, M. H., & Dahlin, T. (2002). A comparison of the gauss–Newton and quasi-Newton methods in resistivity imaging inversion. *Journal of Applied Geophysics*, *49*(3), 149–162. https://doi.org/10.1016/S0926-9851(01)00106-9

Martorana, R., Fiandaca, G., Casas Ponsati, A., & Cosentino, P. L. (2009). Comparative tests on different multi-electrode arrays using models in near-surface geophysics. *Journal of Geophysics and Engineering*, *6*, 1–20. https://doi.org/10.1088/1742-2132/6/1/001

Papadopoulos, N. G., Tsourlos, P., Tsokas, G. N., & Sarris, A. (2006). Two-dimensional and three-dimensional resistivity imaging in archaeological site investigation. *Archaeological Prospection*, *13*(March), 163–181. https://doi.org/10.1002/arp.276

Papadopoulos, N. G., Tsourlos, P., Tsokas, G. N., & Sarris, A. (2007). Efficient ERT measuring and inversion strategies for 3D imaging of buried antiquities. *Near Surface Geophysics*, *5*(6), 349–361.

Phillipson, D. W. (2012). *Foundations of an African Civilisation: Aksum & the northern Horn 1000 BC–AD 1300* Published in association with the British Institute in Eastern Africa ()*Eastern African Series [13]*. Woodbridge, UK/Rochester, NY: James Currey.

Ricci, L., & Fattovich, R. (1987). Scavi archeologici nella zona di Aksum. *A Seglamien Rassegna di Studi Etiopici*, *30*, 117–169.

Schmid, T., Koch, M., Diblasi, M., & Hagos, M. (2008). Spatial and spectral analysis of soil surface properties for an archaeological area in Aksum, Ethiopia, applying high and medium resolution data. *Catena*, *75*, 93–101. https://doi.org/10.1016/j.catena.2008.04.008

Schneider, R. (1976). Documents épigraphiques de l'Éthiopie – V. *Annales d'Éthiopie*, *10*, 81–93.

Sernicola, L., Capra, D., Gaudiello, M., Kribus, B., & Phillipson, L. (2015). Archaeological expedition at Aksum (Ethiopia) of the University of Naples "L'Orientale" – 2013 field season: Seglamen. *Newsletter di Archeologia CISA*, *6*, 267–279.

Sernicola, L., Makonnen, H., & Phillipson, L. (2013). Archaeological expedition at Aksum (Ethiopia) of the Universita Degli Studi di Napoli "L'Orientale". *Newsletter di Archeologia CISA*, *4*, 343–439.

Sernicola, L., & Phillipson, L. (2014). Archaeological expedition at Aksum (Ethiopia) of the University of Naples "L'Orientale" – 2012 field season: Seglamen. *Newsletter di Archeologia CISA*, *5*, 479–506.

Sernicola, L., Phillipson, L., Fattovich, R., Getaneh, A., Capra, G., Giovannone, D., & Moy, R. (2016). Archaeological expedition at Aksum (Ethiopia) of the University of Naples "L'Orientale" – 2014 field season: Seglamen. *Newsletter di Archeologia CISA*, *7*, 223–241.

Shaaban, H., El-qady, G., Khozaym, A., Al-emam, A., & Ghazala, H. (2014). Archaeo-geophysical survey around Itay El-Baroud area, Nile Delta, Egypt. *Archaeological Discovery*, *2*, 45–57.

Stummer, P., Maurer, H., & Green, A. G. (2004). Experimental design: Electrical resistivity data sets that provide optimum subsurface information. *Geophysics*, *69*, 120–139.

Tsokas, G. N., & Hansen, R. O. (2000). On the use of complex attributes and the inferred source parameter estimates in the exploration of archaeological sites. *Archaeological Prospection*, *7*(1), 17–30. https://doi.org/10.1002/(SICI)1099-0763(200001/03)7:1<17::AID-ARP131>3.0.CO;2-O

Urbini, S., Cafarella, L., Marchetti, M., Chiarucci, P., & Bonini, D. (2007). Fast geophysical prospecting applied to archaeology: Results at « villa ai Cavallacci » (Albano laziale, Rome) site. *Annals of Geophysics*, *50*(3), 291–299.

Wilkinson, P. B., Meldrum, P. I., Chambers, J. E., Kuras, O., & Ogilvy, R. D. (2006). Improved strategies for the automatic selection of optimized sets of electrical resistivity tomography measurement configurations. *Geophysical Journal International*, *167*, 1119–1126. https://doi.org/10.1111/j.1365-246X.2006.03196.x

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