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The Applications of Analytic Signal Method in Archaeological Investigations of Part of Lejja Pre-historic Site, South-Eastern Nigeria

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Authors' contributions

This work was carried out in collaboration between all authors. Author AJO designed the study, acquired the archaeo-magnetic data with assistance of author CCO, performed the data analysis and interpretations, wrote the protocol and wrote the first draft of the manuscript and managed literature searches. Author PIEU conducted extensive excavations at Lejja and dated the sites while author CCO supplied the materials on history of the study area. Authors PIEU and CCO also wrote part of the introduction and edited the interpretation aspect. All authors read and approved the final manuscript.

Original Research Article

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ABSTRACT

The attempt to properly date the iron-age Lejja site has been the concern of some archaeologists for the past few decades. The latest archaeological investigations of the area revealed that artefacts could be found at depths below one metre. Excavation of such completely concealed features may involve much futile digging which is prohibited at most locations in the community. To avoid discontinuity of the research resulting from environmental restrictions, we have adopted a more environmentally friendly approach; that is, geophysical mapping of the artefacts before excavation. Archaeo-magnetic data was acquired on regular 1 by 1 metre grid covering a total area of 2400 square metre using proton precession magnetometer (Geometrics model G-856AX). The analytic signal software used for inversion of the field data was first validated using synthetic data obtained from Rao and Babu model. The result revealed presence of some archaeological features, perhaps, a prehistoric iron smelting furnace and a mound nearby, both remaining in-situ and buried at same depth of 1.76 metres. Also revealed were two other

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smaller features which were, most likely, iron smelting slag blocks buried at depths of 1.2 and 1.56 metres. However, permission was not granted for excavations that were needed to confirm the above results.

Keywords: Iron-age; artefacts; excavation; analytic signal; inversion; model.

1. INTRODUCTION

Ejuona site is an integral part of Lejja archaeological site, a well known prehistoric iron smelting site in south-eastern Nigeria [1,2,3,4]. The researcher [5] who dated Lejja site as earlier than 2000 B.C. emphasized the need for intense archaeological research in the area to recover more dates and clarify some claims about the origin of the iron smelting technology in the sub-Saharan Africa [6,7,8]. The earlier excavations that were done in other parts of Lejja made use of exposure of the outlines of the artefacts, particularly furnaces, caused by erosion cuts [1,5]. Since a large number of such features are more deeply buried and may not be noticeable on the surface due to sedimentations that occurred over the centuries, their excavation can only be done through untargeted digging which may not only face environmental restrictions but may involve futile labour and damages to the cultural features beyond repair. It is therefore advisable that while this scientific method of tracing human history is very essential, it must be applied very selectively. A solution to such problem may be an application of a more environmentally friendly approach (the use of geophysical methods) prior to excavations [9,10,11,12,13]. The geophysical methods are mostly applied in archaeology to define the plan locations and depths of the artefacts. Prominent among such methods is the magnetic method using analytic signal technique.

Analytic signal method is one of the varieties of methods of interpretations that are based on the use of derivatives of the magnetic anomalies to determine causative source parameters such as boundaries, plan locations and depths [14,15,16]. The method does not require knowledge of the direction of magnetisation and therefore it is useful in cases of remanent magnetisation. It is applicable in all regions of the world, but most important at low magnetic latitudes such as Ejuona-Lejja (latitude of about 6º43') where reduction to the pole technique can seldom be applicable due to the increase in the complexity of anomalies from the subsurface sources caused by the vector nature of the magnetic field. The amplitude of the 3-D analytic signal of the total magnetic field displays maxima over magnetic contacts regardless of the direction of magnetisation, and therefore can be used to trace the outlines and compute the depths of magnetic bodies in the prehistoric iron smelting site. The study was aimed at using the detailed magnetic data to determine the spatial locations of any existing artefacts in Ejuona by deploying the analytic signal method. In order to properly interpret the real magnetic data, the purchased software was first validated using synthetic examples. The synthetic data were generated using [17] Algorithm.

2. MATERIALS AND METHODS

A brief review of the analytic signal method is needed for understanding of its applicability in the archaeological site. The 3-D analytic signal A was given by [18] for a potential field anomaly M as:

$$\vec{A} = \left(\frac{\partial M}{\partial x} \hat{a}_x + \frac{\partial M}{\partial y} \hat{a}_y + i \frac{\partial M}{\partial z} \hat{a}_z \right), \quad (1)$$

where $\hat{a}_x, \hat{a}_y$ and $\hat{a}_z$ are unit vectors in the ox, oy and oz directions. The workers [19] showed that the amplitude of the 3-D analytic signal at location (x,y) can be expressed as:

$$|A(x,y)| = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2 + \left(\frac{\partial M}{\partial z}\right)^2}, \qquad (2)$$

where $\frac{\partial M}{\partial x}$ and $\frac{\partial M}{\partial y}$ are the horizontal gradients and $\frac{\partial M}{\partial z}$ is the vertical gradient of the total magnetic field. The analytic signal amplitudes can be easily computed with commonly available computer software. In order to utilize this advantage in locating concealed magnetic sources, [20] derived the relationship between 2-D analytic signal amplitudes and spatial locations of magnetic sources. Such relationship was given by [21] for the amplitude of the analytic signal over 2-D magnetic contact at depth h as:

$$|A(x)| = \frac{\alpha}{\left(h^2+x^2\right)^{½}}. \qquad (3)$$

Also given for magnetic sheet (or dike) and cylinder respectively are

$$|\mathrm{A(x)}| = \frac{\alpha}{\left(\mathrm{h}^2+\mathrm{x}^2\right)} \qquad (4)$$

and

$$|A(x)| = \frac{\alpha}{\left(h^2+x^2\right)^{3/2}}, \qquad (5)$$

where x is the distance along the profile and α (the amplitude factor) is given by

$$\alpha = 2\mathrm{M}\sin\mathrm{d}(\mathrm{I} - \cos^2(\mathrm{I})\sin(\mathrm{D})), \qquad (6)$$

where M is the strength of magnetisation (same as equation 1), d is the dip of the magnetic source, I is the inclination of the magnetisation vector and D is the direction of magnetisation. The authors [21] have emphasized the dependency of the shape of the analytic signal on depth and have stated that the depth to the top of magnetic sources can be determined from the shape of the analytic signal anomaly. They then gave the relationship between depth (h) and the width $x_{½}$ of the anomaly at half the maximum amplitude from equations (3), (4) and (5) as used by [19,22]. The equations are:

$$x_{½} = 3.46h, \qquad (7)$$

$$x_{½} = 2h \qquad (8)$$

and

$$x_{½} = 1.533h \qquad (9)$$

for magnetic contact, dike and cylinder respectively.

In the analytic signal technique, it is typically assumed that the causative sources are near-vertical, step-like geologic structures [19,20,23], in which case, the analytic signal maxima are located directly over the edges of the structures. The technique has been shown to be effective in interpreting subsurface magnetic contacts [20,21,24,25]. That is, the signal amplitudes exhibit maxima over contacts, and thus, can be used to trace the outline of any magnetic body provided source-sensor separation is small [26]. Contact models can therefore be used to approximate most of the very near-surface structures that are encountered in archaeological and engineering surveys.

3. APPLICATION OF SYNTHETIC DATA

A moderate size site of 40 m by 60 m, same as the site chosen at Ejuona, was used as a model for the generation of the synthetic data. In order to give a good trial to the methods of surface location and depth determinations, four discrete sources with volumes between 0.25 m^3 and 1.12 m^3 were assumed with assumed other source parameters such as susceptibility of 0.05, various inclinations and declinations of the magnetisation vector and depth of the sources. A FORTRAN program, based on [17] algorithm, was written using the above parameters (Table 1) and others to generate the synthetic magnetic anomalies. The results obtained were gridded and contoured (Fig. 1.) so as to view the anomaly pattern. The plan view of the source was also superimposed on the magnetic anomaly map so as to assess the proper positioning of the anomaly relative to the source.

Table 1. Magnetic source parameters for the 4-body models

S/N	a_1	a_2	b_1	b_2	h_1	h_2	i_m	d_m	susc
1	25.0	25.5	15.0	15.5	1.0	2.0	-10.0	-10.0	0.05
2	10.0	11.0	30.0	31.0	1.0	3.0	0.0	0.0	0.05
3	35.0	35.7	25.0	25.8	1.0	3.0	0.0	5.0	0.05
4	48.0	49.0	18.0	19.0	1.0	2.0	-8.0	0.0	0.05

Note: a_1, a_2, b_1, b_2, h_1 and h_2 are distances in metrescorresponding with those in Fig. 1. i_m, d_m and susc are inclination and declination of magnetisation vector and susceptibility respectively

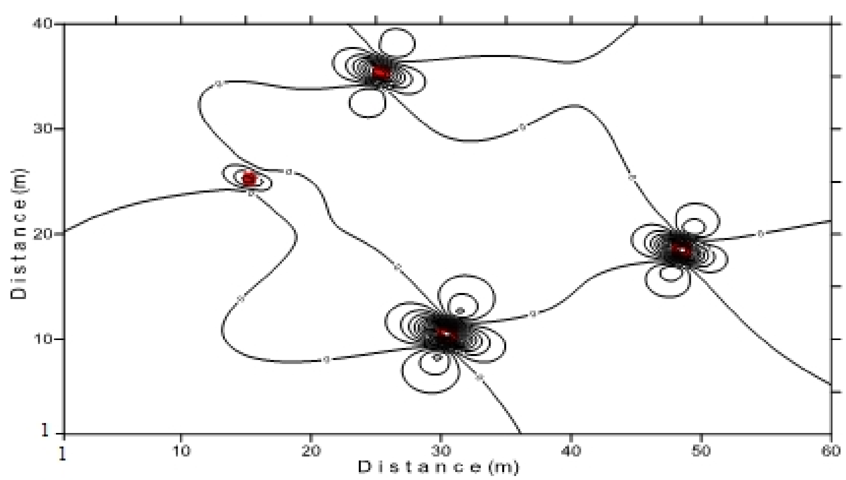

Fig. 1. Calculated magnetic anomalies superimposed on their sources

In the attempt to access the performance of the proposed technique in recovering the model plan locations and depths, the synthetic magnetic anomalies were transformed using the analytic signal technique. The analytic signal amplitudes needed to compute the source depths were obtained by drawing the profiles P-1 to P-4 across the analytic signal anomalies Fig. 2 and the amplitudes were obtained using the Golden software (*surfer*) digitizing facilities. Different orientations of the profiles were used to assess the effect of profile directions on the computed depths. The depths to top of the model sources were calculated using equation 7 (for contact model), where [19,21,22] defined the $x_{½}$ as width of the analytic signal at half the maximum amplitude. The plan locations of the sources were also obtained by scanning the centre of each analytic signal anomaly for the point of maximum amplitude using the *surfer* facilities. The results obtained are shown in Table 2.

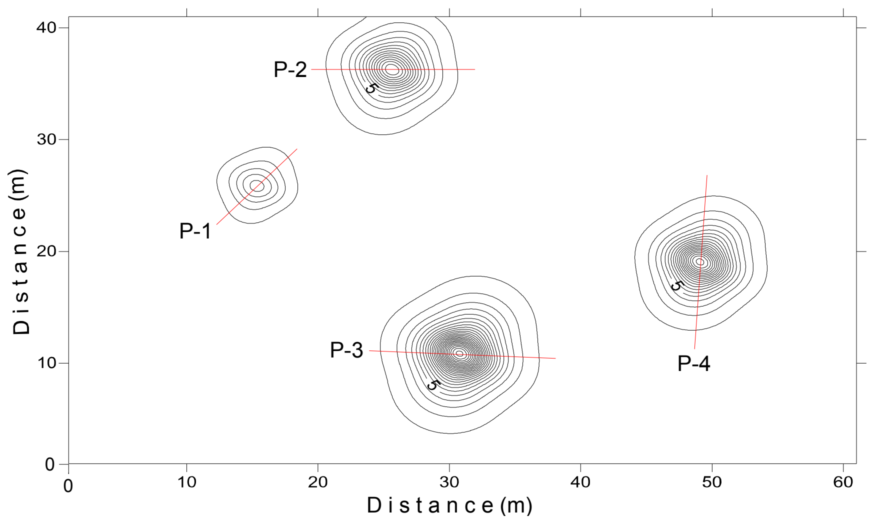

Fig. 2. Mapping the plan locations of the model magnetic sources using analytic signal method

Table 2. Results of the inversion of the synthetic data

Anomaly Number	x(m)			y(m)			Depth(m)		
	Model	Calc	%Error	Model	Calc	%Error	Model	Calc	%Error
1	25.25	25.90	±2.50	15.25	15.38	±0.85	1.00	0.95	±5.00
2	10.50	11.00	±4.55	30.50	30.69	±0.62	1.00	1.06	±6.00
3	35.35	36.42	±2.94	25.40	25.48	±0.31	1.00	1.03	±3.00
4	48.50	49.02	±1.10	18.50	19.13	±3.30	1.00	1.05	±5.00

4. FIELD EXAMPLE

Acquiring the magnetic total field data involved making a grid consisting of a series of measurement points equally spaced along a series of parallel lines. The lines were positioned so as to form a square grid. This type of survey design was used to ensure that the measurement points defined a grid that sampled the magnetic field strength at a uniform spatial density. A base station was also established to make provision for magnetic data reduction. The magnetic total field data were then acquired on a regular 1 x 1 metre grid covering a total area of 40 by 60 square metres in Ejuona village in Lejja archaeological site, south-eastern Nigeria. A proton precession magnetometer (Geometrics' model G-856AX) with resolution of 0.1 nT was deployed with magnetic sensor height fixed at 30 cm above the ground surface.

The acquired magnetic total field data were reduced using the single-step technique developed by [27] and contoured to visualise the anomaly pattern (Fig. 3). The residual field were then transformed by computing the analytic signal amplitudes (Fig. 4) from which the analytic signal shapes obtained were used to calculate the depths to the magnetic sources [19,22]. The surface location of each magnetic source was determined by scanning the centre of its analytic signal anomaly for a position of maximum amplitude using the *surfer* facilities. The results obtained are displayed in Table 3.

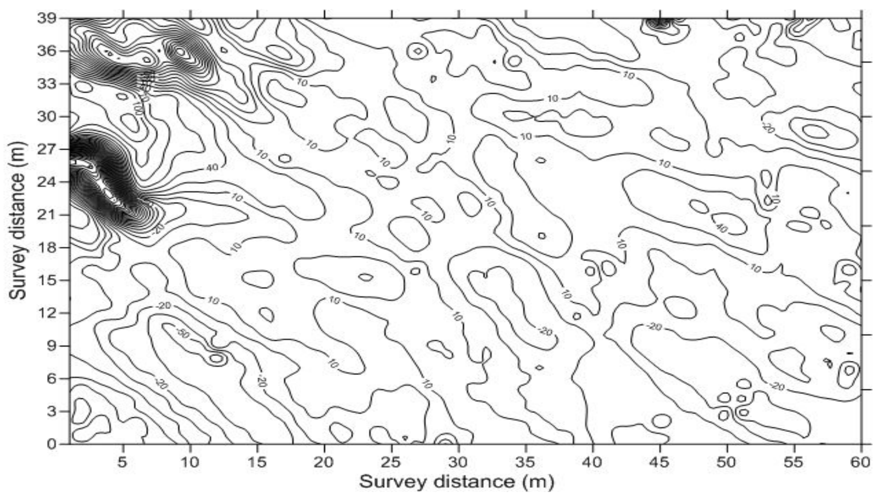

Fig. 3. Residual anomaly of Ejuona data

Table 3. Magnetic source locations in Ejuona village

Anomaly number	x (m)	y (m)	Depth (m)	Error ±(m)	Dist. across anomaly(m)
1	1.10	26.98	1.76	0.24	6.60
2	3.44	35.42	1.76	0.24	3.07
3	8.54	36.03	1.20	0.08	1.92
4	44.69	39.79	1.56	0.21	1.27

5. DISCUSSIONS

The inversion of the synthetic data revealed the minimal error limits of ±0.31 to ±4.55 percent in the model surface locations, and ±3.00 to ±5.00 percent in the model depths of burial of the magnetic sources, thus validating the software in interpreting real archaeological magnetic data. The inversion of the real data revealed that the north-western part of the study area, an area of about 12 m by 20 m, was a major iron smelting activity area. The major analytic signal anomalies (labelled 1 to 3) are noticeable in this small area. The fourth major anomaly (labelled 4) can be found in isolation at the extreme north of the study area.

In order to gain proper understanding of the site, the archaeo-magnetic field of Fig. 3 was upward continued by 0.5 m (Fig. 5). The effects of the very near-surface features which are unlikely to be of archaeological interest were filtered out, revealing the anomaly sequence depicted in the major activity area earlier mentioned. The sequence begins with an anomaly having positive pole to the south (arrow 1) followed by a negative pole to the north (arrow 2). This order was repeated immediately towards the north as indicated by the arrows 3 and 4 of Fig. 5. In this area of study with geomagnetic field inclination of about -10º, the above sequence is an indication of the presence of sources of magnetic field that have positive susceptibility contrasts with their host soils [28,29]. Therefore the analytic signal anomaly (numbered 2) in Fig. 4 appears to be the most archaeologically interesting one in this study area. The result predicts the two separate sources numbered 2 and 3. The earlier source, whose centre has the coordinates (3.44,35.42), has a diameter of about 3 metres, analytic signal amplitude of 56.11 nTm^{-1} and is buried at a depth of about 1.76 metres (Table 3). Immediately to the east of this is the source labelled 3 with the plan position at (8.54,36.03). It has analytic signal amplitude of 59.03 nTm^{-1}, a diameter of about 1.92 metres and buried at a mean depth of about 1.20 metres. The grey colour background (0.0 nTm^{-1}) in Fig. 4, close to the latter source, shows that it was not fired in situ but, perhaps, a repositioned iron smelting slag block which is suspected to be a product of a nearby smelting activity. Based on the above reasons and the predictions of [5], the magnetic source at location 2 (Fig.4) is regarded as a large iron smelting furnace with surface location, (3.44,35.42) in metres, and buried at depth of 1.76 metres. The wide-looking diameter of such furnace (3 metres) may be due to long period of firing.

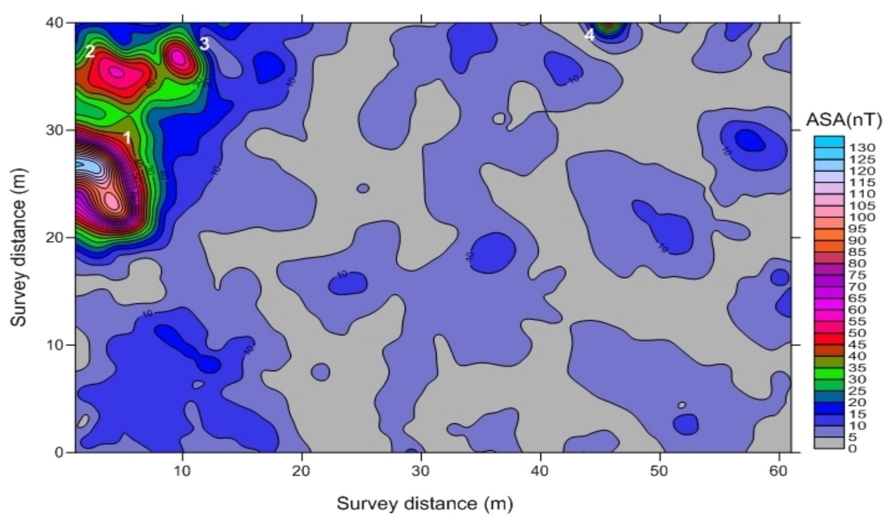

Fig. 4. Analytic signal amplitudes of Ejuona magnetic data

The second major anomaly labelled 1 in Fig. 4 is an elongated, very high amplitude anomaly. Unfortunately, the full size could not be recovered. This problem was noticed at the trial contouring during the field work, but an attempt to recover the whole shape of the anomaly would mean extending the magnetic profiles to cover a nearby main road which was not possible due to vehicular and pedestrian movements. It displays higher analytic signal amplitude (125.69 nTm^{-1}) than the sources at locations 2 and 3 (Fig. 4), and occupies an estimated area of about 65 m^2 with the assumption that about 66% of it has been mapped. It can therefore be inferred from the analytic signal result that it is a mound, made up of debris such as small-size slag blocks, blooms, broken fired clay tools (e.g., tuyère), charcoal, etc., that were thrown out of the near-by furnace site and allowed to cool in the ambient geomagnetic field. The sources at locations 3 of Fig. 4 and location C of Fig. 5 are, most likely, another repositioned iron smelting slag block and a bloom respectively.

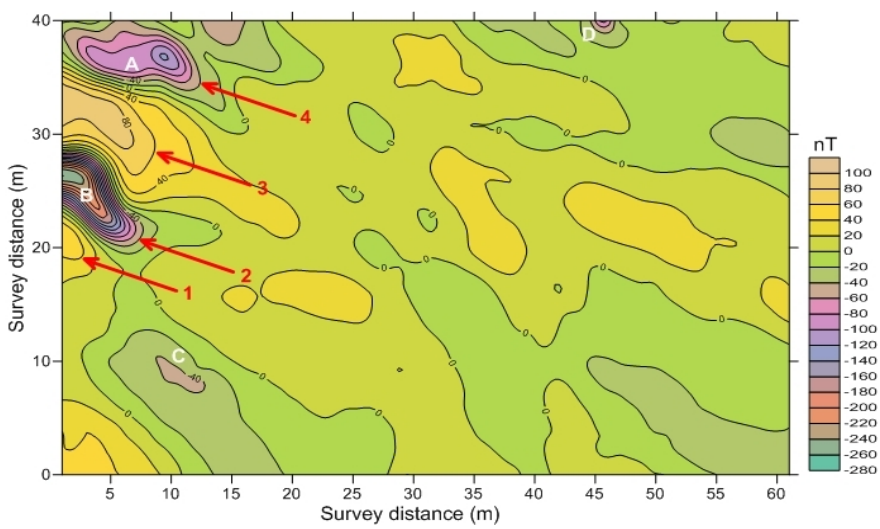

Fig. 5. Ejuona data upward continued by 0.5 metre and showing only major anomalies: A, B, C and D. (Coordinates of the origin: 7º22.75' E, 6°42.75' N)

6. CONCLUSION

Ejuona village is among the locations popularly known for pre-historic iron smelting activities in Lejja archaeological site. Piles of slag blocks at the village square confirm this claim, but the iron smelting furnaces and other smelting materials are no longer visible at the surface. The search for these, using conventional archaeological techniques has been the concern of some archaeologists for the past few decades [1,3,5]. The need for applications of the modern search tools has been adequately discussed under the introduction. One of the fastest and most dependable techniques in such site is the magnetic prospecting method. In this study, the magnetic data was inverted using the analytic signal technique.

The application of analytic signal method to magnetic data is similar to reduction to the pole (RTP) procedure [30,31] in which the anomaly is made to seat directly over its source. Since RTP is seldom applied at the low magnetic latitudes [32,33,34]. Other workers [35], in the development of the MAGMAP (software) using fast Fourier transform (FFT) processing system, achieved a similar result that is now used in MagPick to map subsurface sources. MagPick, the processing software used in this study, has the facility for interpreting the magnetic data using the analytic signal technique. The initial attempt was the validation of the software using synthetic examples.

The inversion of the real magnetic data at Ejuona village revealed presence of iron smelting furnace, a mound and a slag block at the north-western part of the study area. The results revealed the first two relics as remaining in situ at depth of 1.76 metres while what appeared to be a displaced slag was found close to the furnace but at the depth of 1.20 metres below the ground surface. The other feature of archaeological interest might be a slag block remote from the activity zone, at location (44.69, 39.79) and at depth of about 1.56 metres. The above computations would have been more affirmed if integrated techniques were applied. This could not be achieved due to logistic problem and confirmation through excavation was also not possible due to environmental restrictions.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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