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Research Article

Analysis of the Magnetic Anomalies of Buried Archaeological Ovens of Aïn Kerouach (Morocco)

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Aïn Kerouach is one of the most important archaeological sites in the northern part of Morocco. The main buried archaeological ruins in this area were surveyed in 1977 using magnetic prospecting. This survey highlights the mean anomalies that are related to potteries ovens built to the Marinid dynasty that governed Morocco from the 13th to the 15th century. In order to find the maximum depth of the sources, we computed the enhanced downward continuation filter in order to highlight the magnetization contrasts in high detail, depending on the depth downward included in the computation. The main goal is providing a reliable mapping to observe the ovens in depth by shifting the data below the plane of measurement. The results showed an important depth variation of the main ovens given by the original magnetic map and revealed others. Indeed, the downward continuation process applied to analyze the magnetic data shows its efficiency to highlight the buried archaeological structures.

1. Introduction

Morocco is a country with very ancient origins. The territory offers a huge cultural heritage called "Tourath" of high educational value that dates back to the ancient era of many empires and invaders groups. The Moroccan history began about 1,100 BC by the Phoenicians followed by the Carthaginians (814-146 BC) and the Romans (146 BC-429 AD), respectively [1]. Over time, the Romans fell apart, letting Arabs take over with the introduction of Islam to Morocco since 705. Afterwards during this epoch, Morocco soon broke up into different kingdoms; the first was the Adarissa (788-974), followed by the Almoravids (974-1147), the Almohads (1147-1248), the Marinids (1248-1465), the Wattasids (1465-1555), the Saadians (1554-1659), and later the Alaouites (1664-present day) [2–4].

Specific studies on historical Morocco in the pre-Roman, Roman, and Islamic era were initiated since 1950 and continue today with several works [5–8]. All these studies revealed that the Moroccan cultural heritage is spatially distributed in different regions. Nine famous Moroccan archaeological sites have been adjudged by UNESCO to be important historical-cultural resource (Volubilis, Historic City of Meknes, Ksar of Ait-Ben-Haddou, Mogador, Medina of Fez, Medina of Marrakesh, Titawin, Portuguese City of Mazagan, and Historic City of Rabat) (Figure 1). These wonderful historical sites show the way early people lived their day-to-day lives in pre-Roman, Roman, and Islamic era.

Nowadays, the increasing interest in preserving the Moroccan archaeological sites requires the integration of multidisciplinary studies. In this paper, we have essentially focused on an archaeological site called "Aïn Kerouach" situated at the borders of the Rif belt in the north of Morocco. This site is at a distance of about 60 km from Fez (Figure 1). It dates back to the Middle Ages, especially to the Marinid period more than a thousand years ago.

According to Hassar-Benslimane [9], the site was discovered in 1976 during a drilling groundwater activity by the residents of Maarif and Kerouach villages. These activities revealed the presence of some architectural and decorative structures and highlighted the first remains of materials used for building (Figure 2(b)). Most of these structures are similar to those existing in ancient cities such as Fez, Marrakesh, Meknes, Sale, and others historical Moroccan cities [10].

A magnetic survey was carried out in 1977 at the southeast of the discovered decorative structures (Figure 2(a)) [11]. The

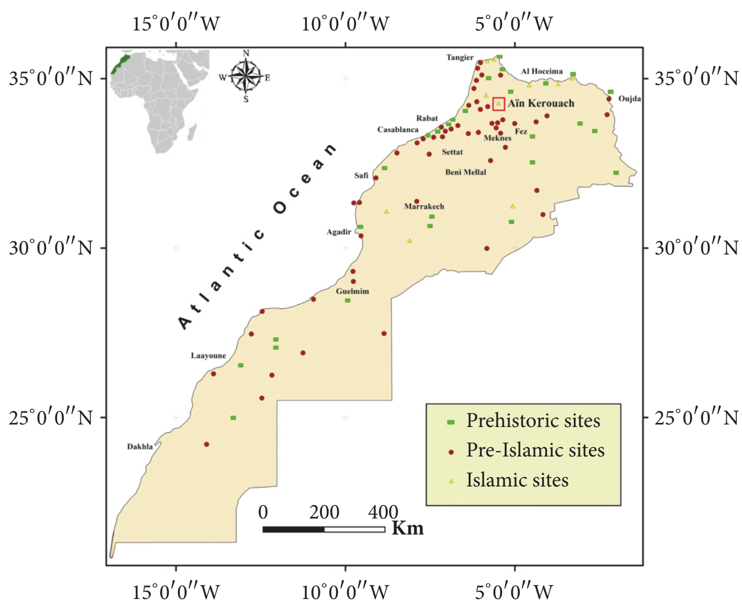


Figure 1: Main Moroccan archaeological sites. The site of Aïn Kerouach is highlighted with red rectangle [13].

purpose of this survey was to try to reveal possible archaeological buried objects near the structures already discovered.

The idea of doing a magnetic survey was encouraged by the presence of some magnetic mineral included in the buried archaeological objects. Hence, the archaeological structures such as kilns, furnaces, slag blocks, fire-places, ceramics, bricks, and tiles possess significant magnetic susceptibility contrast. The intensity of magnetization produced may vary depending on the magnetic properties of the materials where these structures were constructed.

According to Tatyana [12], buried ovens filled with earth, pottery, or ashes will show positive magnetic anomalies with an amplitude range from 20 to 50 nT. These anomalies are due to the magnetization of certain ferromagnetic oxides, grains of iron, magnetite, and hematite, present in the baked clay of the ovens. When the kiln is heated above the Curie temperatures of the grains the latter become demagnetized and as the kiln cools the grains acquire a magnetic potential.

Furthermore, other archaeological structures such as wells, cisterns, or pits filled with ashes, fragments of ceramics, and burnt soil may create positive anomalies of about 50-75 nT. The structures made of earth typically create magnetic anomalies in the range of 1-20 nT. The walls of sandstone or limestone can give negative magnetic anomalies with values ranging from -2 to -20 nT. Streets covered with tiles, of ceramic pots, or metal slag, may give positive anomalies with amplitudes of about 10-100 nT; Pithoi, associated with ancient Greek sites, give positive anomalies of a greater intensity 50-100 nT [14, 15].

2. Materials and Methods

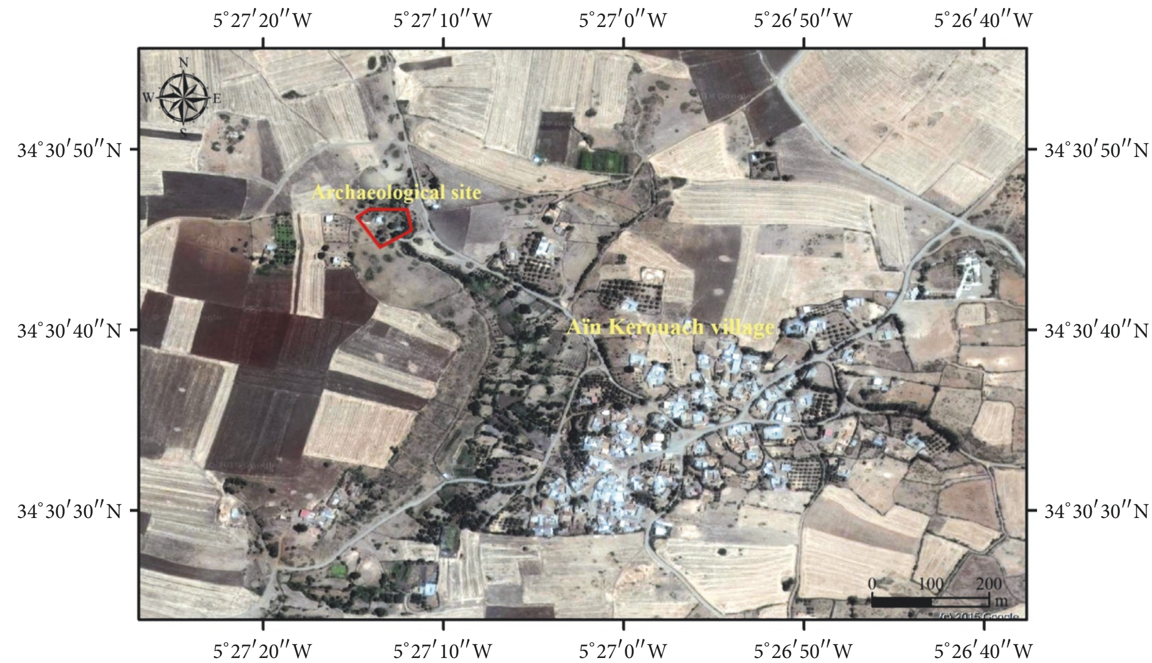
The magnetic survey was undertaken by means of a G-816 geometric scalar magnetometer (Figure 3) [16, 17]. The data were measured in gamma (ɣ) unit, where 1 ɣ = 1 nT (nanotesla).

Within our study project, it is necessary for the anomalies/objects (paper map format) (Figure 4(a)) to be available in an assigned digital format (Figure 4(b)) [18]. This activity is the most important aspect to provide extreme flexibility of our magnetic anomalies.

In this technical brief, we describe the digitization process of this nonpublished magnetic anomalies map provided by Dr. Patrice Cressier [11]. Firstly, we undertook the scanning of our magnetic map. Then, the digitization has been performed using a metric coordinate grid by preserving the original information quality. We have digitized (100x67) magnetic data manually and processed them to be useful as a tabular XYZ file.

In order to eliminate the error introduced by the process of digitization operation, we have geo-referenced the available map using 4 calibration points (0, 0), (0, 30), (30, 45), and (45, 0) as indicated on the corners of the resulting map (Figure 4). Afterwards, we have evaluated the overall residual error which is of the order of 5×10^{-5} m. Taking into account the scale of the digitized map (1 cm⟶5 m), the real value represented on the map is 0.025 m, which is smaller than the dimension of the interpolation grid of $0.45 \times 0.45\,m^2$. Therefore, when digitizing, the intervals of the values of anomalies and their position will not be affected or distorted.

The magnetic map has described positive anomalies of elongated and nearly semicircular shapes located mainly in the southwestern part of the area, with more modest negative anomalies immediately around the main positive signals. According to Cressier [9], the three main magnetic anomalies of amplitude higher than 20 nT are associated with buried ceramic ovens “baked” located at a few centimeters below the ground. This assumption coincides with the interpretation given by Tatyana in the section above, which suggests that the rooms containing ovens filled with earth, pottery, or ashes will be seen in magnetic maps as positive anomalies with an intensity of 20-50 nT.

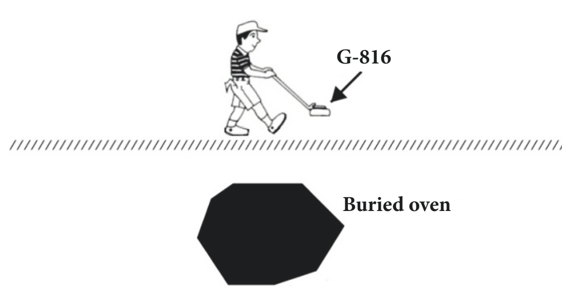


(a)

(b)

Figure 2: Archaeological site of Aïn Kerouach: (a) Google Earth® view of the archaeological site; (b) photographs of some discovered decorative structures [9].

(a)



(b)

Figure 3: Materials and method used in the survey: (a) G-816 geometrics scalar magnetometer; (b) the magnetic prospecting.

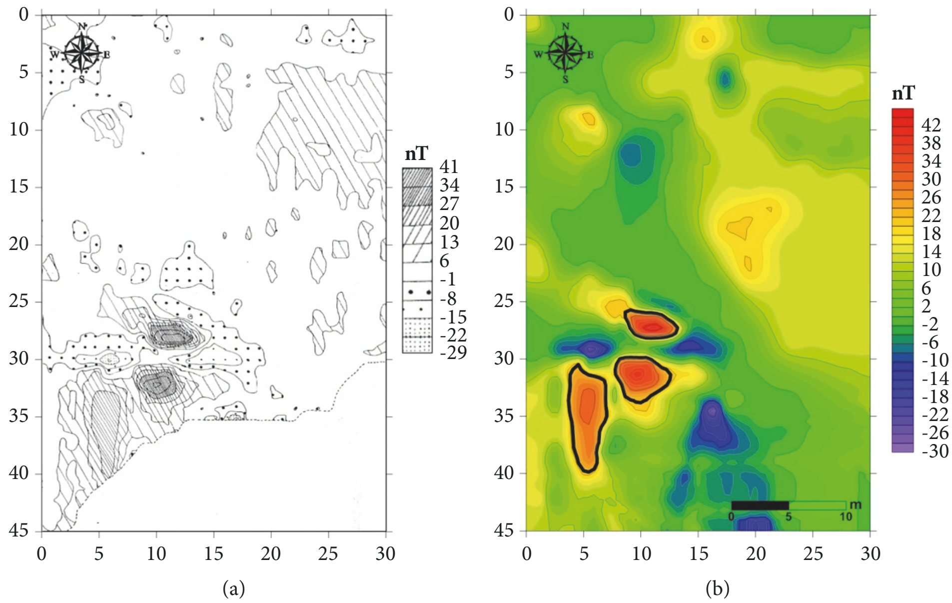


Figure 4: Magnetic map of the archaeological site of Aïn Kerouach: (a) original map; (b) gridded map.

Although these magnetic anomalies provided clear results since we could locate three buried ovens, the analysis of these anomalies requires the employment of new processing tools. In this study, we chose to use the downward continuation filter in order to determine clearly the topographic position and the maximum depth of these anomalies. This approach of analysis was applied extensively in many studies and scientific researches [19–23].

3. Methodology of Analysis

Interpretation of magnetic data is the process of extracting information on the position and extent of buried ruins in the ground [24–26]. In the present case, the buried ruins were essentially the potteries ovens. The amplitude of an anomaly may be assumed to depend on the mass of the body with altered burned material which, in turn, corresponds to recognizable magnetic contrast from surrounding rocks. If the body has the same magnetic susceptibility as the neighbor rock, no anomaly will be detected.

The magnetic map may be considered the sum of a scalar potential set assumed to be harmonic everywhere except above the ovens. Downward continuation filter will amplify the effect of the deep structures and enables us to separate the effect of neighbor sources. This technique allows us to find the depth to the roof of the body without confusing with other structures.

The desired potential anomalies of the sources can be continued mathematically downward to any horizontal plane [27]. The solution of the observed anomalies may be built up using the following equation:

$$\sum_{f=-n/2}^{n/2} \exp^{[2\pi\pi i(z_0-z_1)/\lambda]} \qquad (1)$$

where z is the targeted depth; for $\Delta_z = z_0 - z_1$ the downward continuation operators are as follows:

$$\sum_{f=-n/2}^{n/2} \exp^{[(2\pi 2\pi i f/\lambda)_z]} \qquad (2)$$

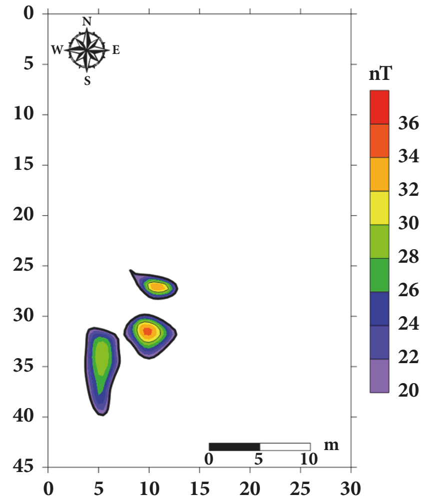
According to (2), the downward continuation filter of the magnetic anomaly increases exponentially with depth. The effectiveness of this method is important since the anomalies can be clearly visible and well smoothed [28, 29]. It would be easy to discern the buried archaeological ruins of the study area.

4. Results and Discussion

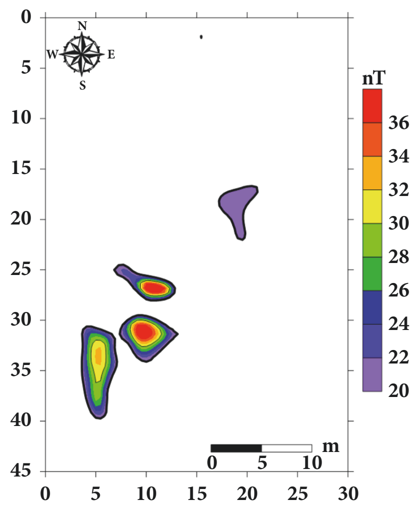
The magnetic anomalies data over this archaeological site were firstly gridded by kriging to an interval of 0.45 m in both x and y directions. Afterwards, the downward continuation filter was applied to the data to highlight the significant signal at different selected plans below the surface. The residual heading error is removed by using a moving average filter which proved satisfying results.

For the best delimitation of our targets, the magnetic data anomalies were downward continued vertically by a step depth of 0.2 m. The buried ovens were outlined in depth down to 1.2 m. This filter mathematically transforms our magnetic data acquired from the surface to the values that would have been measured at the different selected planes.

Figure 5 is a plot of the different filtering responses maps. On inspection of our processed data, the contours values of these maps are restricted to an interval range between 20 nT and 37 nT. This way enables isolating anomalies of interest of higher amplitude from the total data in order to delineate the anomalies/objects highlighted in the original map (Figure 4). Except for these higher amplitude anomalies, the rest of



(a)



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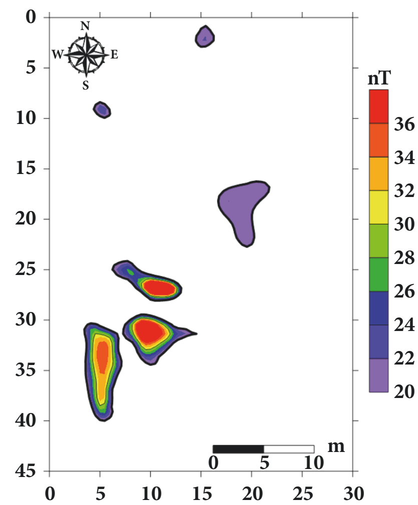

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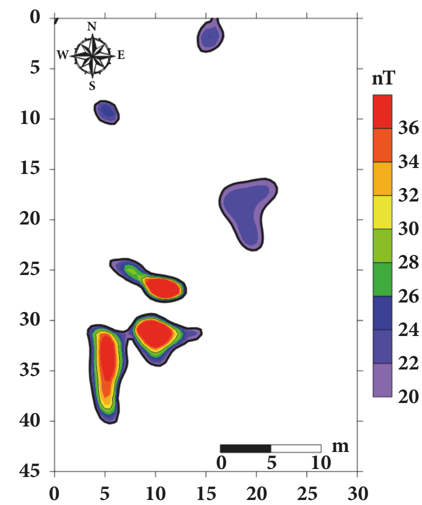

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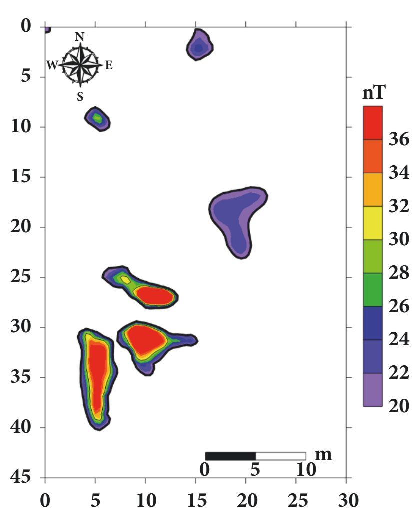

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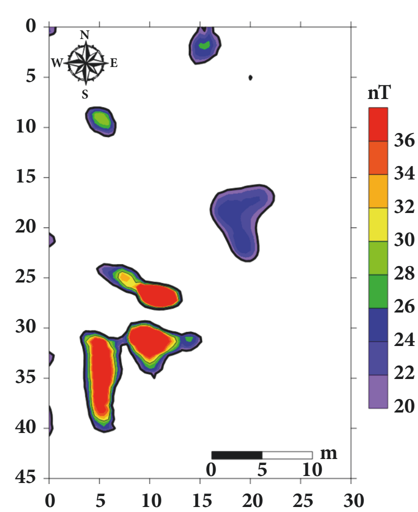
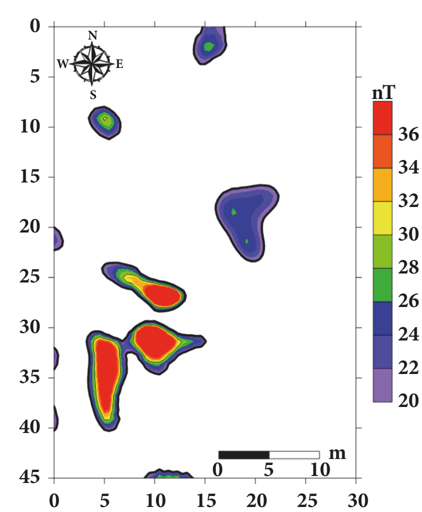


(f)



(g)

Figure 5: Downward continuation responses of the original magnetic data (contour interval = 2 nT). The original data (a) are downward continued to six different levels: (b) 0.2 m; (c) 0.4 m; (d) 0.6 m; (e) 0.8 m; (f) 1 m; (g) 1.2 m.

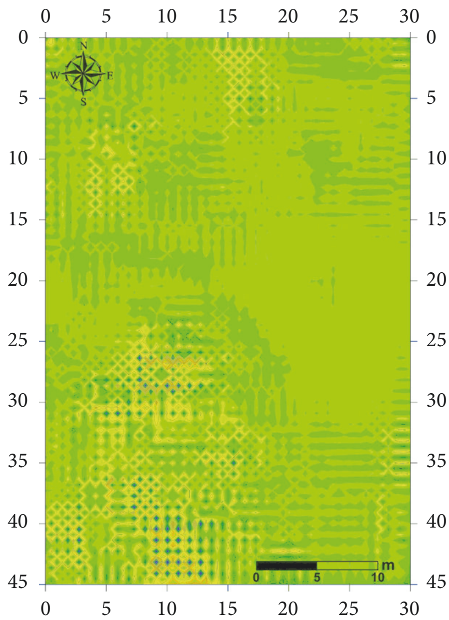


Figure 6: Response of the magnetic data downward continued to 1.4 m.

our historic site surface still containing short wavelength anomalies may be associated with debris.

This analysis produced different characteristic anomalies and confirmed our expectations for anomalies caused by the buried ovens with spatial dimensions of several meters. It gives us sharper images, so that, as depth increases, we can estimate the field of ovens and outline the field for other new sources of anomalies. This filtering process highlights anomalies edges and provides more accurate determination of their extents. It is clear that the fitted maps establish an influence of deeper features of different anomalies. The linear feature gradually appears and becomes more prominent as the anomalies continue downward.

Furthermore, we emphasize that, at 1.4 m, the filtering response produces unreliable and erratic results (Figure 6). The anomalies become clumsy and the interpretations turn out to be consequently impossible. Consequently, this depth limit is thus assumed to be the basis of the buried ovens.

5. Conclusions

In this work, we describe the results regarding the integration of downward continuation filter for reanalyzing the magnetic anomalies of the archaeological site of Aïn Kerouach region (northern Morocco). This filter appears as a powerful tool to define variation of the buried archaeological ovens in depth with a very clear shape which was revealed on the maps.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this work.

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