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Magnetic investigation at the Amorium archaeological site, Emirdağ, Afyon, Turkey

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Abstract: *Amorium is well-known as an important city in the middle of the Anatolian plateau that flourished mainly during the Byzantine period. The archaeological site is located approximately 70 km to the northeast from the modern provincial capital of Afyon. The archaeomagnetic survey was carried out in an area located in the Lower City near the Large Building. The measurements were taken by means of a Geoscan FM 36 Fluxgate magnetometer. The aim was to detect buried archaeological remains. In order to obtain further information about lateral extension of the remains, the boundary analysis technique was used. In this way the maxima of the horizontal gradients that outline the boundaries of the source bodies were computed. Largest maxima points were suggested as the most promising ones for archaeological excavation.*

Key words: *Amorium, Archaeomagnetic, Boundary Analysis, Horizontal Gradient, Maxima*

INTRODUCTION

The ancient and medieval city of Amorium is located in eastern Phrygia (the modern Turkish province of Afyon). Part of the site is now occupied by the village of Hisarköy, which lies within the administrative district of Emirdağ. Amorium is a very ancient settlement, and findings point out that it dates back at least to the Early Bronze Age. This prehistoric settlement was undoubtedly located where the mound or Upper City now stands. The city of Amorium includes a large man-made mound. Amorium was perhaps occupied as early as the Bronze Age but it was certainly inhabited during the Hittite and Phrygian periods. Although it does not figure prominently in the early history of Anatolia, it may be identified with a Hittite town, called Aura. During the seventh century AD, Amorium played a major administrative and military role, principally because of its strategic position on the main route between Syria and Constantinople. During the 'Dark Ages', it was the military centre of the Byzantine province or 'theme' of Anatolikon (Lightfoot, 1997). Amorium has been under excavation since 1988, first directed by Prof. R.M. Harrison and since 1993 by Dr. Chris Lightfoot. The topographic map of the site is shown in Fig. 1.

Information about the position, depth, and extension of buried archaeological remains can be obtained by means of geophysical investigation, which is carried out easily and quickly on the surface without disturbing or damaging the buried archaeological features (Yiğit, 2005). The magnetic method is the most frequently used geophysical technique for archaeological investigations all over the world. Detecting buried objects (fireplaces, kilns, burnt soils) by magnetic measurements is one of the well established archaeogeophysical applications (Breiner, 1974). Because of these advantages and taking into account existing archeological information about the site, the magnetic method is suitable for this investigation. The aim of this magnetic survey was to obtain further information about the size and extent of the archaeological features. In addition, the boundary analysis method was applied to the gradiometric data.

THE METHOD

The method of the horizontal gradient maxima was proposed by Cordel and Grauch (1982, 1985) for estimating the location of abrupt lateral changes in magnetization or mass density.

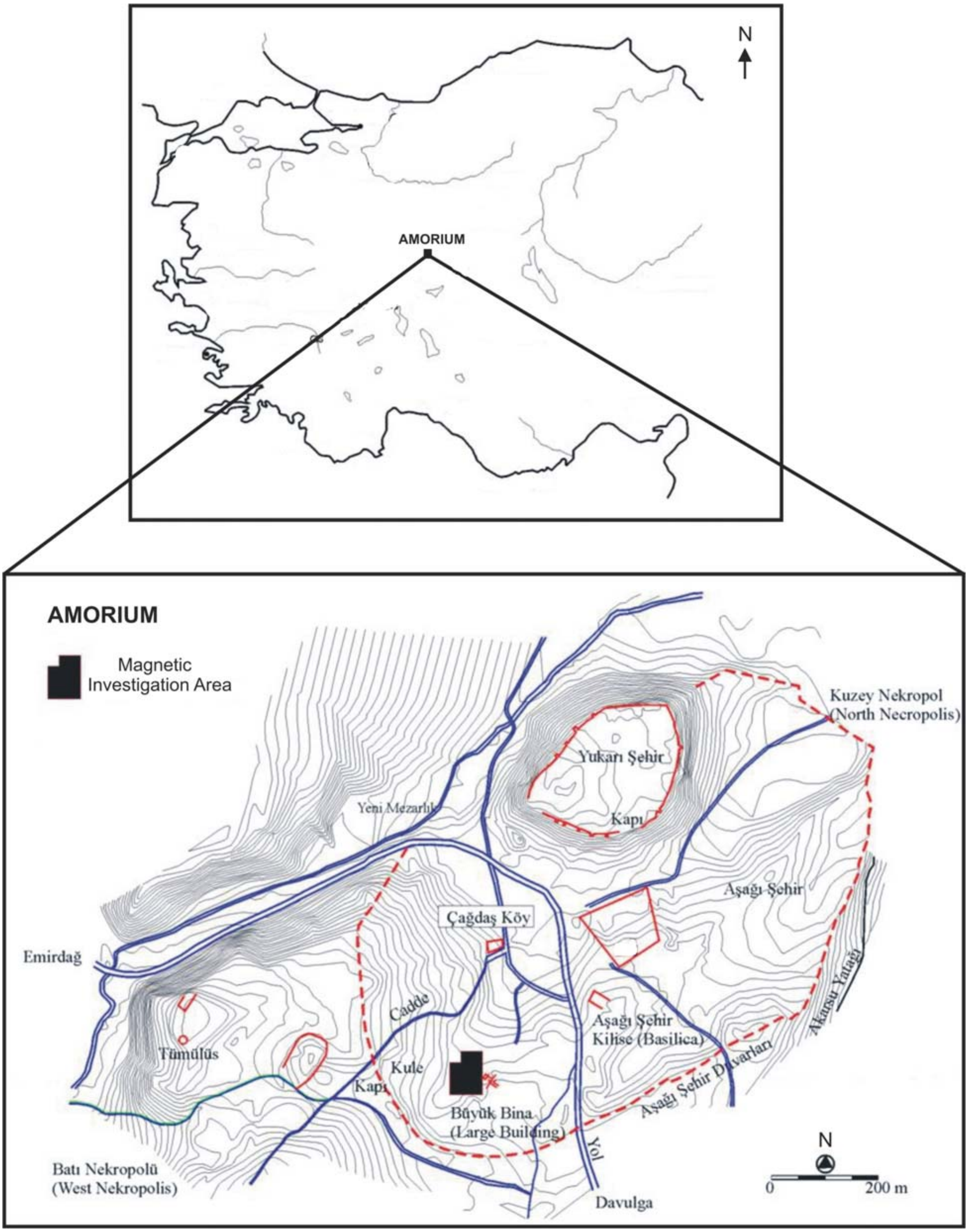

FIG. 1. The location and topographic map of the site.

The method is based on a three-step procedure. First, the pseudogravity transform (Baranov, 1957) is applied to the magnetic data. By using the pseudogravity transform, the apex of the magnetic anomalies is shifted over the source body and the distortion due to the earth's magnetic field can easily be removed. A pseudogravity transformation is useful in interpreting magnetic anomalies, not because a mass distribution actually corresponds to the magnetic distribution beneath the magnetic survey, but because gravity anomalies are in some ways more instructive and easier to interpret and quantify than magnetic anomalies (Blakely, 1995).

At the second stage, the horizontal gradient of the pseudogravity anomaly is calculated (Fig. 2). Shallow bodies produce gravity anomalies with maximum horizontal gradients located nearly over their edges. Thus, at this stage the proposed method transforms the magnetic anomalies into ridges of maximum pseudogravity gradients that may overlie the edges of causative magnetic bodies (Blakely and Simpson, 1986). The final step involves comparing the value at each grid node to its eight nearest neighbors (Fig. 3). In order to find whether the $g_{i,j}$ is the maximum horizontal gradient or not, its eight nearest neighbors must be known and the following conditions should be satisfied:

$$g_{i-1,j} < g_{i,j} > g_{i+1,j} \tag{1}$$

$$g_{i,j-1} < g_{i,j} > g_{i,j+1} \tag{2}$$

$$g_{i-1,j-1} < g_{i,j} > g_{i+1,j+1} \tag{3}$$

$$g_{i+1,j-1} < g_{i,j} > g_{i-1,j+1} \tag{4}$$

A counter N is increased by one for each satisfied inequality. Hence N ranges from 0 to 4 and provides a measure of the quality of the maximum; N is called as the significance level of the maximum. For each satisfied inequality, the location and magnitude of the maximum are found by fitting a second-order polynomial through a trio of points (Blakely and Simpson, 1986).

If the first inequality is satisfied, the location of the maximum relative to the position of $g_{i,j}$ is given by:

$$x_{\max} = \frac{-bd}{2a} \tag{5}$$

where:

$$a = \frac{1}{2}\left(g_{i-1,j} - 2g_{i,j} + g_{i+1,j}\right) \tag{6}$$

$$b = \frac{1}{2}\left(g_{i+1,j} - g_{i-1,j}\right) \tag{7}$$

and d is the distance between grid nodes. The value of the horizontal gradient at $x_{\max}$ is given by:

$$g_{\max} = ax_{\max}^2 + bx_{\max} + g_{i,j} \tag{8}$$

If more than one inequality is satisfied, the largest g_{max} and its corresponding $x_{\max}$ are chosen as the appropriate maxima for that grid node.

GRADIOMETRIC SURVEY

Magnetic measurements were collected using the gradient method. Use of the gradient, rather than the total field, emphasizes the shallow sources, reduces regional gradients and removes drift (Young and Droge, 1986). The gradiometric measurements were taken using a Geoscan FM 36 Fluxgate magnetometer (sensitivity of 0.1 nT/m) and grid spacing of 1 m. Data acquisition was performed along parallel survey lines toward the north. Readings were stored in the data logger of the magnetometer and transferred to the computer by means of a RS232 connection cable. A portion of the grid with spoil heaps containing ash and debris from the nearby excavation area, was not scanned.

Following data acquisition, the magnetic gradient map (Fig. 4) was generated. This map exhibits a series of elongated magnetic anomalies. The next step involves pseudogravity transformation and calculation of the horizontal gradient. Then, a computer program devised by Blakely (1995) was used to search for maxima. In the computer program there are seven significance levels. By testing this method on synthetic magnetic data, it has been suggested that the third significance level produces the best results (Doğan and Ateş, 1998; Ekinci, 2005; Ekinci and Kaya, 2006). For this reason the third significance level was used in this study.

The horizontal gradient enhances the anomalies which are present on the magnetic gradient map. The elongated anomalies to the southwest of the horizontal gradient map (Fig. 5) are considered to be man-made features according to the archaeological evidence. The maxima of the pseudogravity horizontal gradient, are displayed in Figure 6. The size and color of the symbols denote the magnitude range of the horizontal gradient according to the legend (Fig. 6).While computing the magnitude of the horizontal gradients, maxima may be so prevalent that some of the smaller and perhaps less significant values of g_{max} must be discarded (Blakely, 1995). Therefore, less significant and smaller values are disregarded in this study.

The magnetic signals originating from potential archaeological remains were enhanced with the use of these analytic signal techniques (Fig. 6). High amplitude anomalies observed at the investigation area may originate from buried Byzantine archaeological features, which are considered large and shallow. These structures are built by a mixture of bricks and limestone. In particular, two parallel linear anomalies to the southwest highlighted with red circles are attributed to the ruins of the Byzantine walls (Fig. 6). The scattered high amplitude anomalies may result from metallic materials or burnt objects such as pots. The circular high amplitude anomalies indicate potential location of rubbish pits, kilns or fireplaces. The black arrows depict the most promising locations for archaeological excavation.

CONCLUSIONS

The horizontal gradient map of the pseudogravity anomalies provides an enhanced image of the magnetic gradient measurements from Amorium archaeological site. In particular, the maximum values of this image are utilized in the interpretation of the magnetic gradient map. Taking in account archaeological evidence, the circular anomalies are attributed to kilns, rubbish pits and fireplaces, while the elongated ones to wall remains. The maximum values (greater than 1 pseudo mgal/m^2) are highlighted with red circles in Figure 6. On this map the elongated and circular anomalies marked with black arrows indicate the most promising locations for archaeological excavation. Pseudogravity transformation followed by horizontal gradient computation aids the interpretation of magnetic data. Accordingly, this strategy is suitable for archaeogeophysical surveys performed by the magnetic method.

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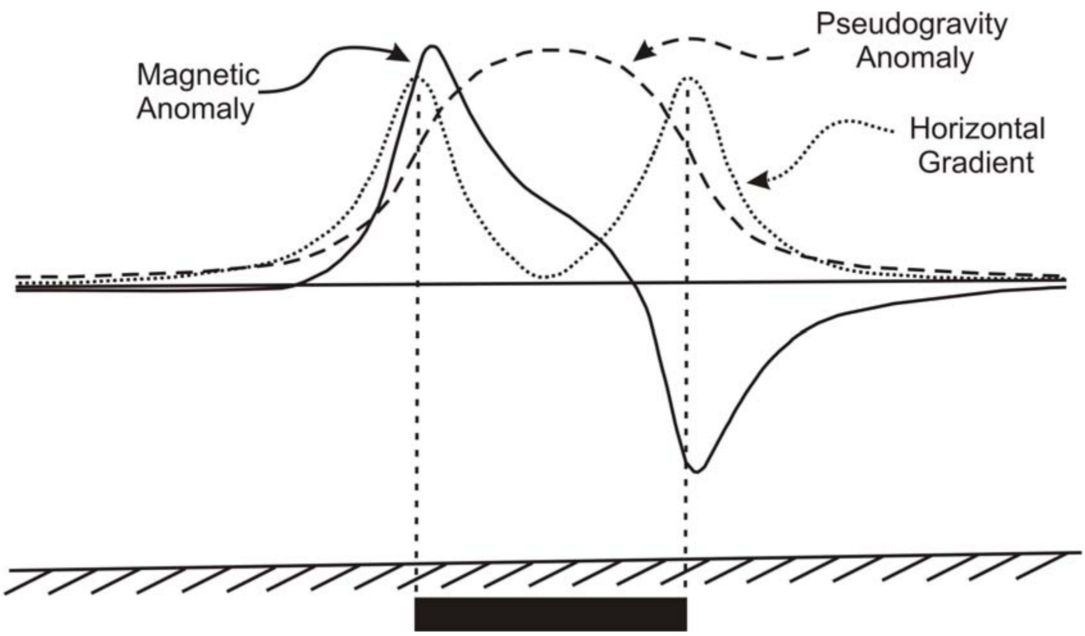

FIG. 2. Magnetic anomaly, pseudogravity anomaly and horizontal gradient of the source structure (Blakely, 1995).

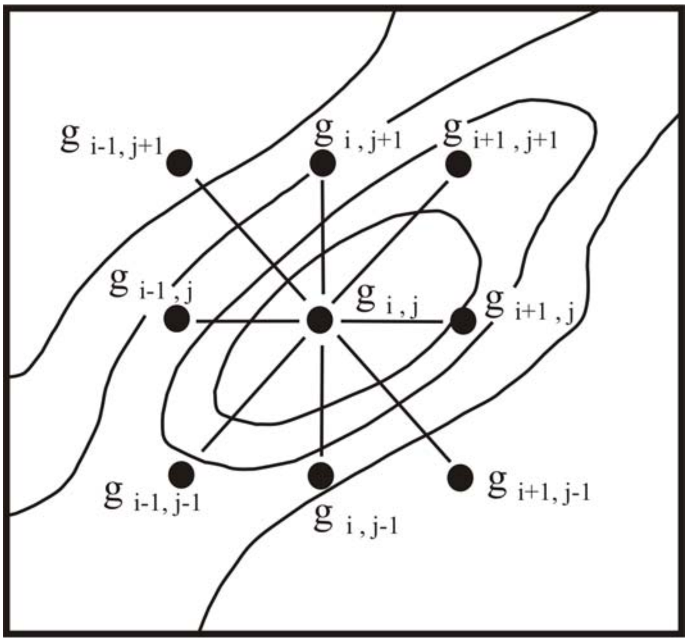

FIG. 3. Location of grid nodes used to search for a maximum around $g_{i,j}$ (Blakely and Simpson, 1986).

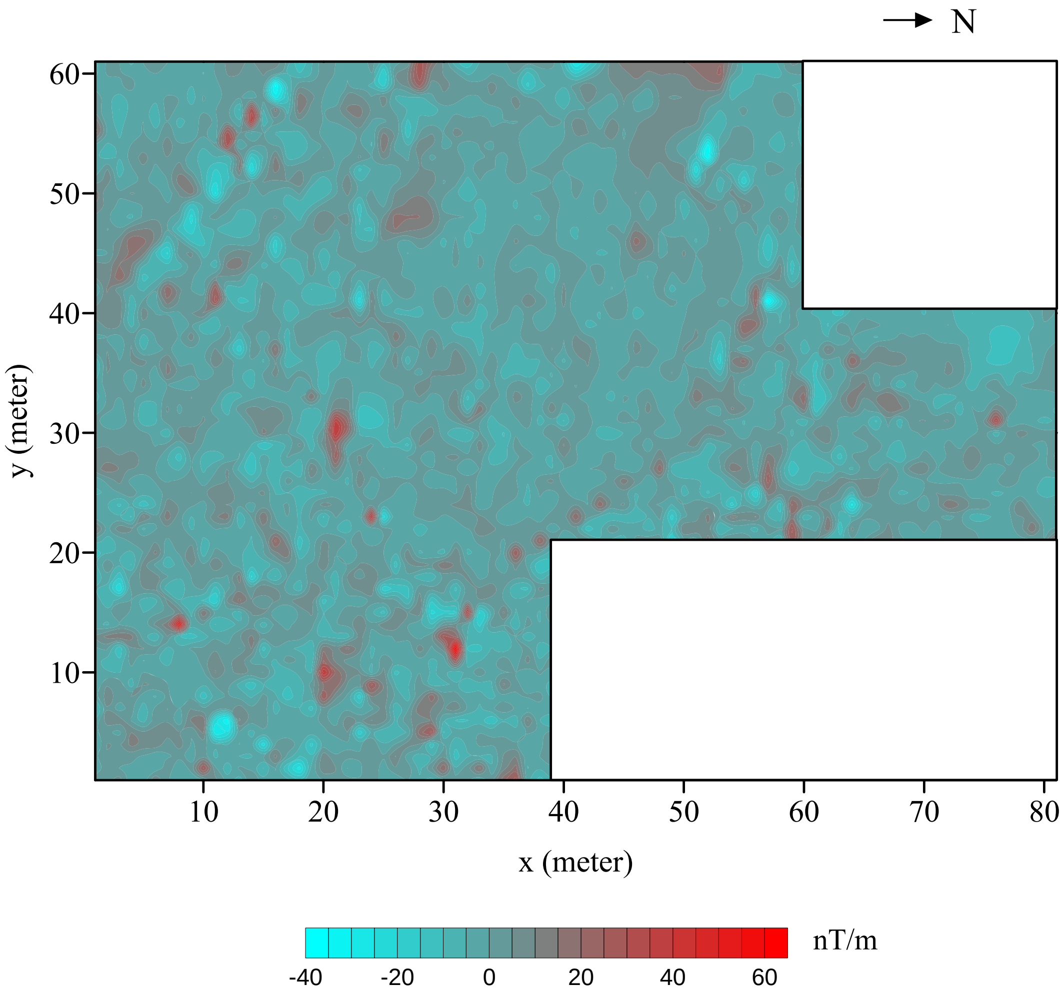

FIG. 4. Magnetic gradient map of the area under investigation.

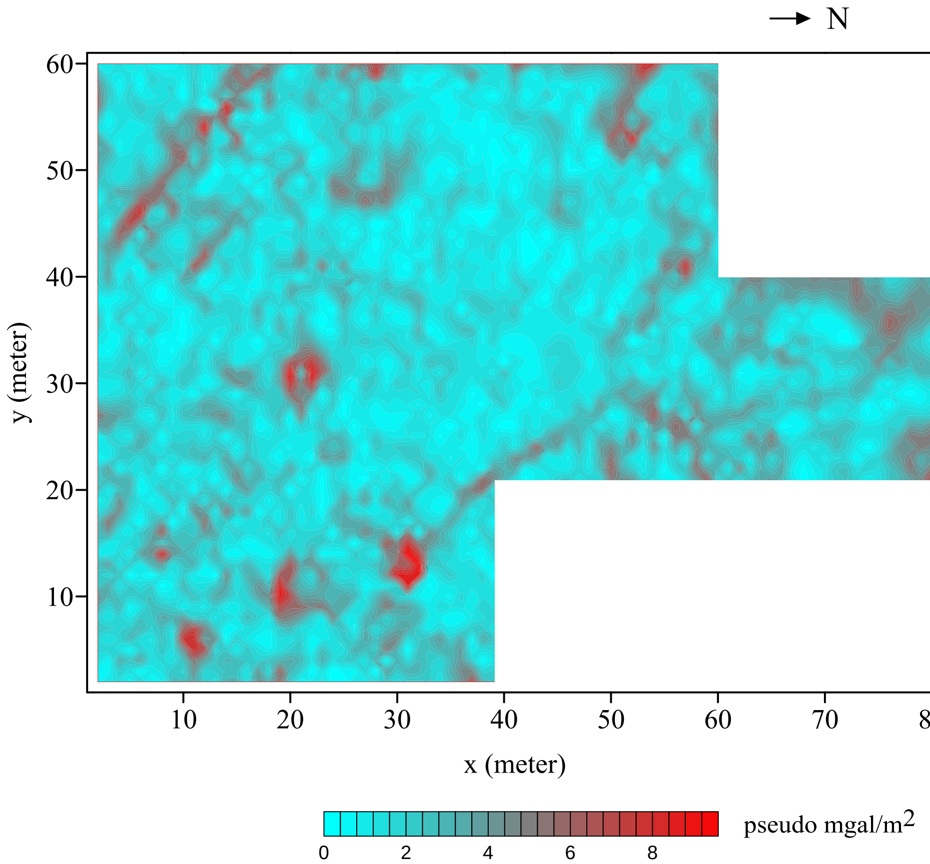

FIG. 5. Horizontal gradient of the pseudogravity anomaly of the area under investigation.

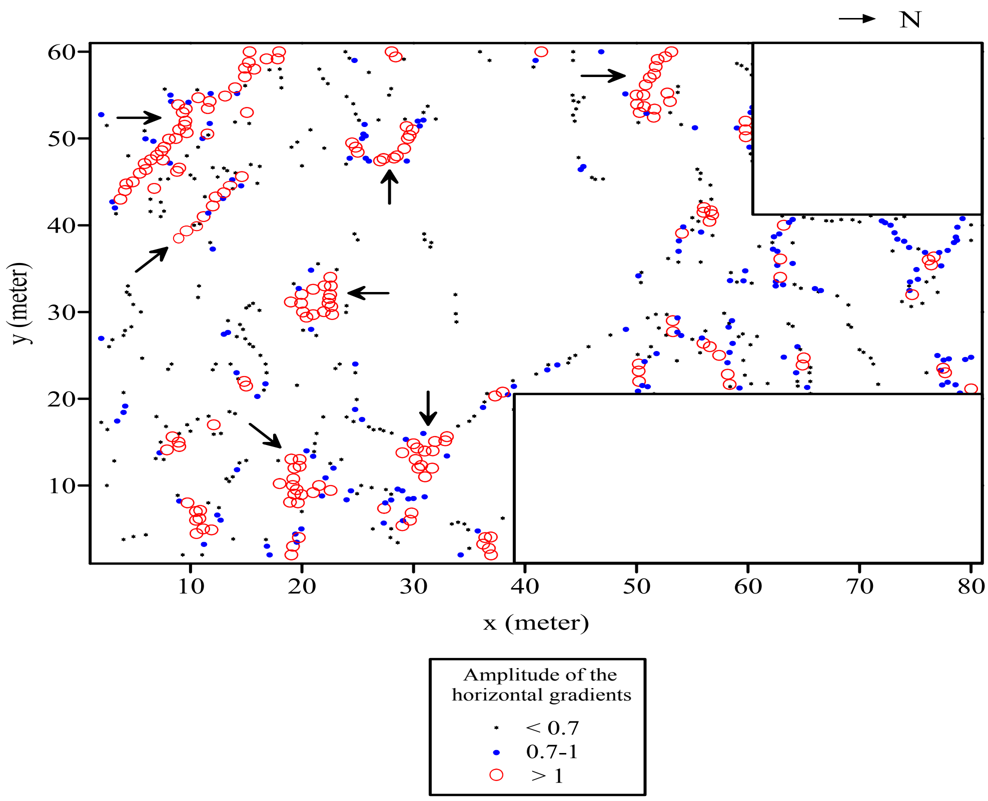

FIG. 6. Maxima of the pseudogravity horizontal gradients for the investigation area. Black arrows depict the most promising locations for archaeological excavation.

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