FORWARD MODELLING OF MAGNETIC ANOMALIES IN ARCHAEOLOGICAL GEOPHYSICS: A NEW SOFTWARE TOOL

A. Schettino, A. Ghezzi
School of Science and Technology – Geology Division, University of Camerino, Italy

Introduction. Although magnetic methods are generally considered among the most important non–destructive techniques in Archaeology, in most cases their usage limits to the acquisiton of vertical gradient data and their direct interpretation in terms of walls or other archaeological features, often without the support of an accurate geophysical analysis. Disadvantages in the acquisition and direct archaeological interpretation of gradient data include the following issues: 1. in most cases the location of a buried artifact is laterally displaced with respect to the corresponding anomaly; 2. important information about the physical properties of an object, which could have archaeological meaning, is ignored; 3. information about the burial depth cannot be easily obtained; 4. nearby objects generate complex anomalies (by the superposition principle) that cannot be interpreted by the simple visual inspection of gradient maps. Finally, Tabbagh (2003) showed that the reduction of anthropogenic disturbances and time variations of the geomagnetic field using appropriate filters gives better results compared to gradiometer measurements.

Here we describe an approach to magnetic prospecting and analysis in Archaeology, which is based on the acquisition of total field data, their reduction to magnetic anomalies, and a computer–assisted analysis of the resulting data set. Our new software tool, *ArchaeoMag*, allows for the first time to reconstruct the geometry and magnetization pattern of a buried settlement through a trial–and–error procedure based on classical forward modelling algorithms. It also allows to determine whether an artifact has been burnt and eventually the approximate time of this event. In the next sections, we first review a method of acquisition and processing of magnetic data from an archaeological site. Then, we describe the operation of *ArchaeoMag* and the basic steps in forward modelling of archaeological anomalies. Finally, we will discuss the potentiality of this approach in difficult situations.

Methods. In a typical high–resolution magnetic survey, total field magnetic data, $T(x,y)$, are usually acquired along a set of survey lines. In the case of moderately disturbed days (K_p = 4) or when the data acquisition requires several hours, it is good practice to correct the data for the daily variations of the geomagnetic field through a levelling procedure. In this instance, it is possible to start with the rapid acquisition along a transverse tie line $\mathbf{T}_0$ that crosses the entire survey area. These data can be considered instantaneous readings at time $t = 0$, because $\mathbf{T}_0$ is generally travelled in only 1–2 min in the case of archaeological surveys. Then, the survey is performed normally following the survey lines. This method allows to build a diurnal drift function starting from the crossover errors $\varepsilon_i(t) = T_i(t) - T_i(0)$. In most cases, the diurnal drift curve can be obtained fitting a cubic polynomial. After the standard pre–processing step, this curve is then subtracted from the raw data to remove the diurnal variations.

The first processing step after despiking, drop–out removal, and levelling should be the calculation of total field values at regular grid locations through a gridding algorithm. Although the general method to obtain magnetic anomalies $\Delta T(x,y)$ from total field data $T(x,y)$ is simply that of subtracting the reference field intensity $F(x,y)$ at the same location, so that $\Delta T(x,y) = T(x,y) - F(x,y)$, this approach does not generally provide anomalies that are representative of archaeological features. In fact, in this instance the magnetic anomalies will be the expression of an anomalous field $\Delta \boldsymbol{F}(x,y)$ that includes two sources. A major source, which is not relevant in archaeological studies, is associated with crustal magnetization and has magnitudes of the order of tens to hundreds nT. The signal associated with archaeological objects is generally much smaller, with rms magnitudes not exceeding few tens nT. Consequently, in this instance the procedure to calculate magnetic anomalies from total field data is slightly more complicate, because it is often necessary to isolate a very small–amplitude signal from the observed data. In our approach, magnetic anomalies are calculated subtracting an N degree trend surface from the total field grid value $T(x,y)$:

$$\Delta T(x,y) = T(x,y) - \sum_{n+m\leq N} a_n b_m x^n y^m \qquad (1)$$

Eq. (1) can be justified noting that the Earth's magnetic field is harmonic in the region outside the Earth's surface, thereby it has continuous derivatives. Consequently, in any sufficiently small survey area it can be represented by a Taylor's polynomial series with constant coefficients.

Calculation of model anomalies. The computer program *ArchaeoMag* is designed to operate on UTM georeferenced maps of archaeological anomalies, although in can be also used in local (survey) coordinates. The program assumes that the anomalies have been determined through the correct application of Eq. (1) or a similar method of total field data reduction. In other words, it assumes that the magnetic anomaly amplitudes reflect the true magnetization of the buried archaeological features.

In addition to specifying input grids, the user selects a color scale for the representation of the magnetic anomalies and some ambient parameters, which include sensor height, the geomagnetic field parameters (F,D_0,I_0), and the soil volume susceptibility χ_0 in SI units. Reference field declination, D_0, and inclination, I_0, are used to calculate model anomalies starting from anomalous field vectors, while the field intensity, F, is used with the soil susceptibility and the susceptibility of the buried objects to determine the induced component of magnetization $\boldsymbol{M}_I$. This approach clearly requires a preliminary soil sampling and analysis through a magnetic susceptibility meter. Finally, the survey area parameters (corner coordinates and map resolution) are calculated automatically by the program after the specification of an input magnetic anomaly grid.

ArchaeoMag allows to define four classes of shapes, corresponding to common archaeological features: 1. spheres (magnetic dipoles), 2. rectangular prisms, 3. generic vertical prisms, and 4. stairways. For any object, the program allows to specify the minimum and maximum burial depths, the magnetic susceptibility, χ, a cutoff distance beyond which the program does not calculate anomalies (for computing time optimization), and a remnant magnetization vector

(M_R,D_R,I_R). The program calculates automatically the induced magnetization vector, $\boldsymbol{M}_I$, and the total magnetization vector, $\boldsymbol{M}$, by the following equations:

$$\boldsymbol{M}_I = \frac{\chi - \chi_0}{\mu_0}\boldsymbol{F} \equiv \frac{\Delta\chi}{\mu_0}\boldsymbol{F} \qquad (2)$$

$$\boldsymbol{M} = \boldsymbol{M}_I + \boldsymbol{M}_R \qquad (3)$$

Methods of forward modelling. Modelling of any specific archaeological feature by one of the basic *ArchaeoMag* shapes should start with a guess about the burial depth and with a characterization of the NRM component, which is predominant in most of the situations that can be studied by magnetic methods. The burial depth influences the lateral width of an

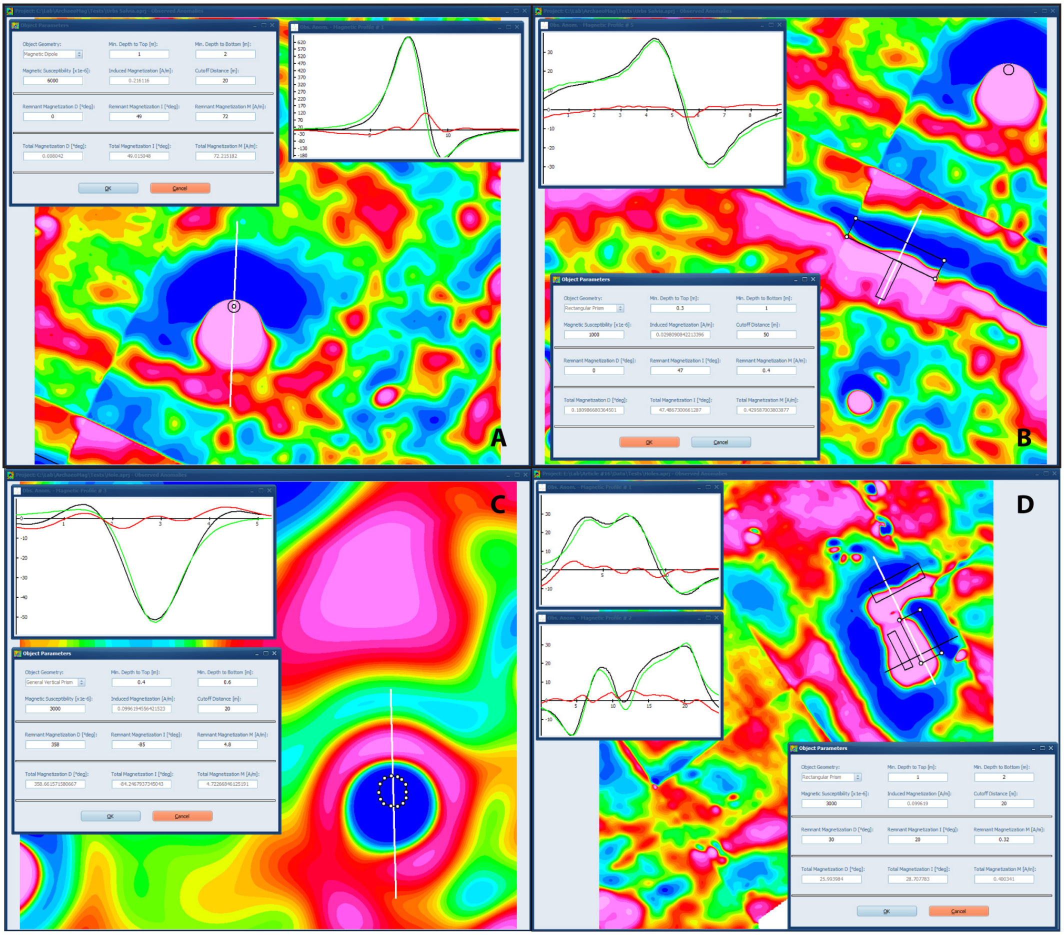

Fig. 1 - Four examples of archaeological anomalies that can only be modelled by sources with a significant component of remnant magnetization. The magnetic profiles show observed and model anomalies (black and green lines, respectively), and the error curve (observed - calculated, in red) along selected traces (white lines). The buried objects arc indicated by black lines and white dots. Model parameters are listed in the object properties dialog boxes. A: A strong dipole anomaly whose peak exceeds 620 nT, most probably a furnace (Powell *et al.*, 2002). B: AT - structure, probably representing a combination of a segment of a long and 2m large WNW-ESE oriented wall and a transversal smaller wall. C: A small cylindrical structure, 70 cm diameter by 20 cm height, characterized by a very anomalous inclination (I = –85°) of remnant magnetization. D: A composite anomaly, resulting from the superposition and coalescence of the anomalies associated with three distinct buildings. The upper profile refers to the black trace oriented WSW-ENE. The parameters of the selected object (delimited by white dots) are listed in the dialog window. The northernmost feature has D = 30°, I = 5°, M = 1.8 A/m, while the western prism has D = 30°, I = 60°, M = 0.3 A/m.

anomaly, which increases with the top depth z_1, while the presence of a remnant magnetization component can be easily established by the detection of one or more among the following features: 1. A magnetic anomaly amplitude exceeding a few nT; 2. A deviation of the strike of the simmetry axis of a dipolar anomaly from the present day reference field declination, D_0; 3. A deviation of the anomaly shape from the expected shape for the given reference field inclination, I_0. Fig. 1 shows an example of observed anomalies that can be modelled by objects having a remnant magnetization component.

In general, the observation of anomalies associated with induced magnetization requires one or more among the following conditions: 1) a strong susceptibility contrast with the surrounding soil; 2) a random arrangement of natural remnant magnetization (NRM) components (e.g., a random orientation of magnetite grain spins in a paramagnetic matrix, a random build–up of bricks, etc.); 3) a low Koenigsberger ratio $Q = M_R/M_I$, and 4) the absence of nearby objects with a significant NRM component. Examples of archaeological features whose anomalies are dominated by induced magnetization contrasts are: graves, historical iron artifacts (Bevan, 2002), ditches and limestone walls. In contrast, remnant magnetization generally produces much stronger anomalies in materials with high Koenigsberger ratio or, more often, when the archaeological structures are fired materials (e.g., bricks) or materials that have been fired at a later time during historical or natural events. A forward modelling session of any local survey anomaly should start with the selection of an object type (dipole, rectangular prism, or general vertical prism) and the creation of 1–2 magnetic profiles, as illustrated in Fig. 1. At the next step, the user should inspect the magnetic profiles, in particular the error curve, in order to start an interactive trial–and–error procedure and determine a magnetization model that can explain

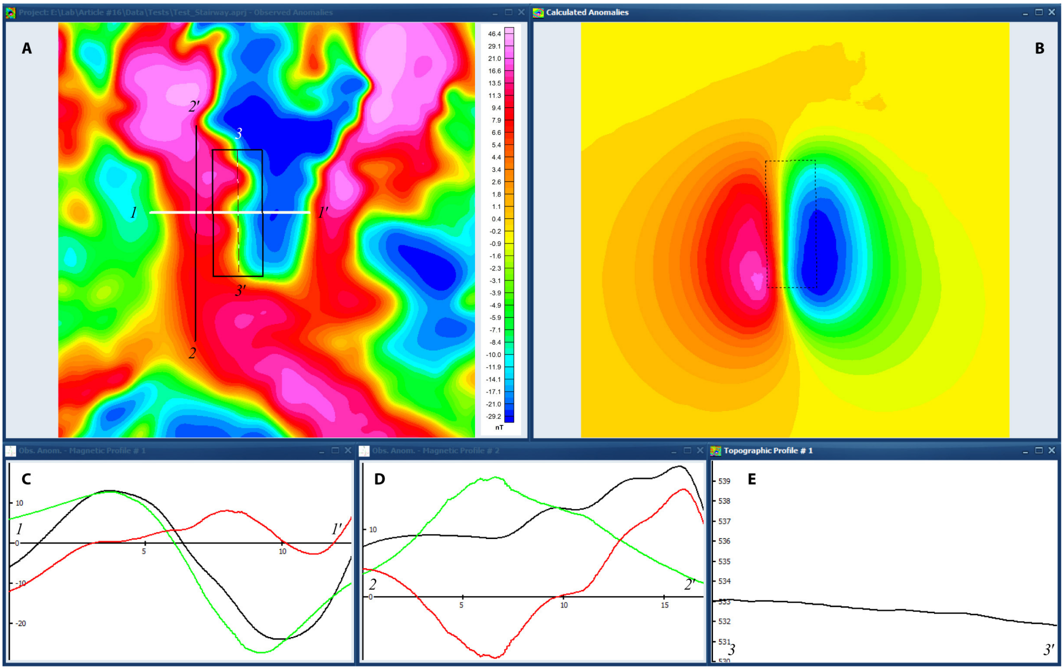

Fig. 2 - A rectangular prism model of observed anomalies (A) along the hill slope (Antigonea archaeological park, southern Albania, Schettino *et al.*, 2017). These data were acquired 0.5 m above the terrain. The average soil susceptibility was $\chi_0 = 500\text{x}10^{-6}$, while the ambient field parameters were: $D_0 = 3.95°$, $I_0 = 56.72°$, $F = 46336.00$ nT. Panel (B) shows the model anomalies. calculated assuming $\chi_0 = 3000\text{x}10^{-6}$, $z_1 = 2$ m, $z_2 = 3$ m, and a NRM vector wih parameters $D = 90°$, $I = -20°$, $M_R = 0.9$ A/m. Panels (C) and (D) illustrate magnetic profiles with model and observed anomalies (green and black curves, respectively), and the error curve (in red). Finally, Panel (E) shows a N-S topographic profile through the prism.

the observed magnetic signal. At each iteration, the NRM parameters and eventually the depth and size of the object are adjusted to progressively minimize the mismatch between the model and observed anomalies along the profiles. The final result is not necessarily what we could find by direct excavation, because of the intrinsic ambiguity of potential field data. However, the availability of archaeological information can help to constrain materials and depths of the model objects, thereby allowing a realistic reconstruction of a buried settlement.

Discussion. The approach presented above allows to create realistic magnetization models of archaeological sites even in the case of complex topography, granted that appropriate acquisition and processing of total field data have been performed. In *ArchaeoMag*, the observed and model grid anomalies are automatically assigned an orthometric height according to an input digital terrain model for the survey area. Therefore, any object in the model acquires local Cartesian coordinates depending from the burial depth specified at the time of its definition as well as from its UTM coordinates. Thus, it is possible to obtain an automatic terrain correction that accounts for the anomaly field distortion associated with topography. An example of application of ArchaoMag to a situation characterized by rugged topography is illustrated in Fig. 2A. These data were acquired in 2015 along the SE slope of the Jermë hill, southern Albania (Schettino *et al.*, 2017). Apparently, a segment of the western branch of the two positive anomaly stripes could be modelled by a N–S oriented rectangular prism, as illustrated in Fig. 2. This interpretation is partially supported by the E–W profile shown in Fig. 2C. However, the N–S profile (Fig. 2D) shows a northward increase of the observed anomalies, whereas the rectangular prism model predicts the opposite, according to the fact that the southern tip of this structure is closer to the surface than the northern end. As a consequence, the observed anomalies cannot be generated by an object having a flat upper surface. In Fig. 3 an alternative model is proposed, which is based on a stairway structure formed by 12 rectangular prisms. In this instance, the burial depth of each step slightly rises downslope, accounting for the increased rate of accumulation in this direction. Undoubtedly, this model provides a much better fit of the model anomalies to the observed values in N–S direction, as shown in Fig. 3C.

As mentioned above, the possibility to model NRM components in addition to induced

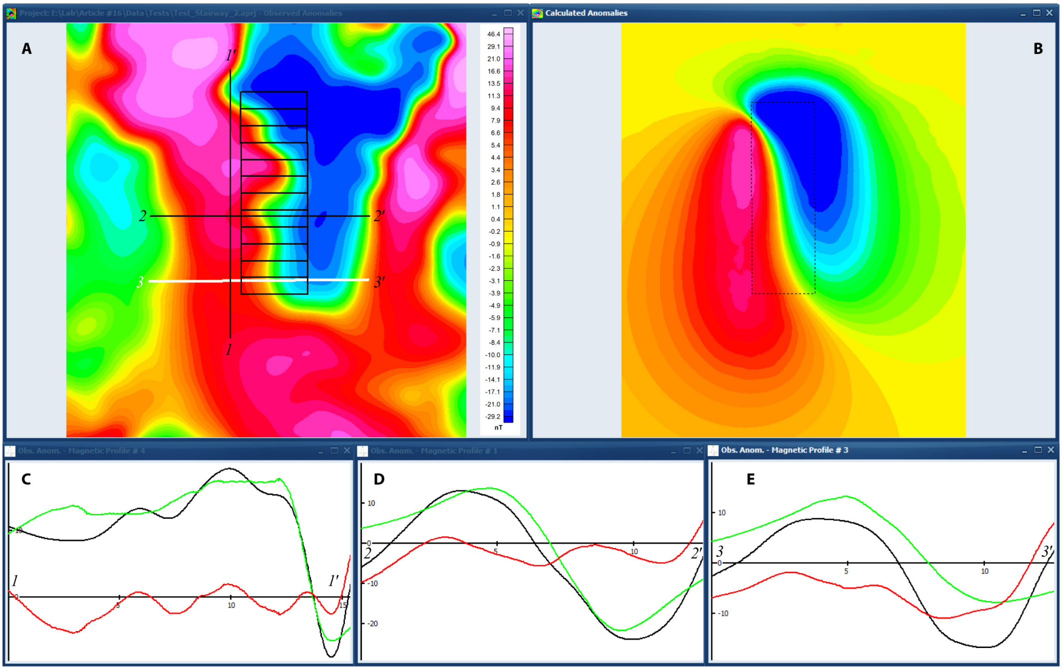

Fig. 3 - An alternative stairway model of the same anomalies considered in Fig. 2A. See text for discussion.

magnetization is an important feature of *ArchaeoMag*, which could be used, in some circumstances, to estimate the age of firing events and help reconstructions of the historical development of a settlement. In fact, when firing is the only event responsible for the acquisition of NRM and it is possible to establish that the artifact has not been moved since that time, we can compare the model NRM declination and inclination with existing master curves of palaeosecular variations, obtaining an age for the magnetization event (e.g., Vigliotti, 2006).

Finally, *ArchaeoMag* allows to export the magnetized blocks as a georeferenced text file that can be subsequently loaded in a GIS and integrated with other data sets for the study area. For example, it is possible to combine or compare magnetization maps with resistivity or GPR data to build an integrated archaeological model. It should be noted that the integration of magnetic anomalies with other geophysical data is not generally a correct procedure, because of the displacement of the objects with respect to the anomaly peaks. Conversely, the exported *ArchaeoMag* blocks provide a model of true archaeological features in their correct position.

Conclusion. In the previous sections, we have presented a new approach to the use of magnetic data in archaeological geophysics, which provides a greater quantity of information and allows an easy integration with other geophysical data. In this approach, total field data are acquired, filtered, and reduced to archaeological anomalies according to standard procedures. Then, an interactive forward modelling software, *ArchaeoMag*, is used to create and edit magnetization models of buried settlements. In addition, it allows to distinguish between induced and NRM components of magnetization, thereby allowing a fine calibration of the model and possibly a dating of firing events. In the present version, three basic shapes and one composite object can be created using the *ArchaeoMag* GUI: Dipoles, rectangular prisms, general vertical prisms, and stairways. Each object can have specific magnetization parameters, size, and burial depth. The shapes can be easily edited, moved, rotated, or resized according to a trial–and–error procedure to obtain a better fit of the model anomalies to the observed values. Finally, *ArchaeoMag* allows to load topographic data, in order to generate model anomalies that can be directly compared with the observed data even in the case of rugged relief.

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