Magnetic mapping and soil magnetic properties applied to the heritage preservation of Roman kilns

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Abstract - As a part of a long-term archaeophysical research project detailed magnetic surveys have been conducted in different areas of Catalonia (N.E. Spain). The main goal of the project was to demonstrate that the magnetic method is very efficient to detect kilns and baked clays of archaeological significance, thus allowing their cataloguing, study and preservation from destruction. The new trends in magnetic methods for archaeological prospecting are moving in the direction of acquiring, processing and interpreting very large data sets. This is being done with microprocessor-controlled instruments and innovative developments in field procedures. This strategy permits the compilation of large numbers of data points in a relatively short amount of time. Large databases mean that larger areas with higher resolution can be covered. Consequently, ground geophysical methods can now provide key information for an accurate and non-destructive examination of the archaeological sites. Different techniques have been applied for processing magnetic data to improve the presentation and recognition of the dipolar signals that are characteristic of kiln's remanent magnetization at intermediate latitudes. Also, soil magnetic properties have been measured to better understand the effect caused by the structures of interest. The subsequent archaeological ploughs have confirmed the usefulness of detailed magnetic surveys and the accuracy of their interpretation.

1. Introduction

Magnetic methods were first used in the 1950s (Belshe, 1957; Aitken et al., 1958), and still now is can be considered as one of the most relevant geophysical methods for the investigation

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of archaeological remains. This is due to the fact that non-invasive subsurface exploration and the production of fast, accurate and cost-effective maps of buried archaeological sites is possible using the magnetic method. Small local anomalies in the Earth's magnetic field result from the contrasting levels of magnetic susceptibility, which exist between infilled structures and the local substratum. This effect is principally due to the varying iron content in the soil forming minerals and also their thermal history.

Particularly, pottery workshops, kilns and different kinds of baked clays are the kind of archaeological structures suitable for magnetic detection. Clay contains some magnetic iron minerals like magnetite, haematite, maghaemite, etc. The spontaneous magnetization of minerals is dependent on temperature in such a way that when they are heated, the spacing between neighboring atomic moments increases until a point is reached where the spontaneous magnetization falls to zero. This temperature is called the Curie temperature. Magnetic grains acquire thermoremanent magnetization (TRM) during cooling from the Curie temperature (about 580 °C for magnetite) to normal ambient temperature in the presence of an external field such as that of the Earth.

According to Scollar et al. (1990), archaeologists can be greatly helped in setting their digging priorities if a suitable geophysical method is used ahead of time. Some of the reasons that justify the use of the magnetic method in archaeological prospecting include:
- magnetic method is not destructive to site integrity;
- large areas can be mapped quickly and inexpensively giving evidence of occupation and activity before excavation is begun;
- magnetic measurements are made more easily than most other geophysical measurements;
- magnetic data can complement excavation data, and allow researchers to understand excavation results within the entire site context.

2. Studied archaeological sites

Results from two archaeological sites are presented and discussed in this paper. The location map of the areas under study is shown in Fig. 1.

Pla d'Abella site (near the town of Navès) is a small depression of about 2 km in diameter located about 100 km NW of Barcelona, between the localities of Cardona and Solsona in the middle of the Catalan Central Basin. The existence of pottery-working kilns in this area was reported by Serra-Vilaró (1925), being the first to produce "Terra Sigillata Hispanica" found in the Iberian Peninsula. Nevertheless, since then the precise location of the settlement was completely missed. Several fruitless attempts were performed to relocate the kilns. From fieldwalking surveys, remains of ceramics and debris were found in the soils surrounding the Pla d'Abella, but the location of the kilns was imprecise.

The Ermedàs site (near the town of Palol de Revardit) is located about 10 km north from the city of Girona and consists of some 2 ha of cereal agricultural field placed on a forest clearing. Before the recent archaeological research the site was almost unknown and only some casual findings were reported from a field survey conducted in 1982.

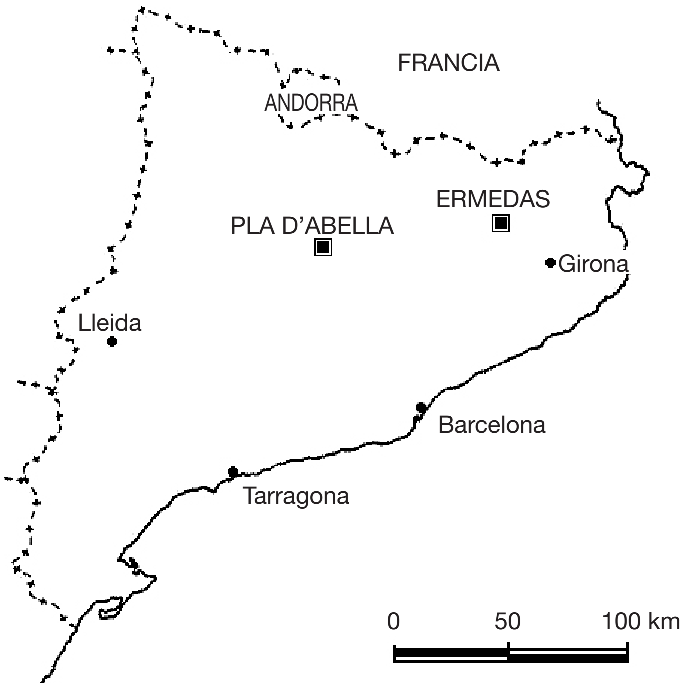

Fig. 1 - Location of the two Roman pottery kilns described in this paper.

3. Magnetic surveys

At the Plà d'Abella site a Geometrics G-816 proton magnetometer was used to measure the magnetic field intensity at each station. The sensibility of the instrument was only 1 nT, but enough for the purpose of the study. The sensor was placed 20 cm above the ground surface and has a compromise between detectability and the high frequency noise produced by pottery fragments and debris spread on the ground. The survey was initially undertaken along profiles directed to the north in a grid of 1 m × 1 m, and subsequently, detailed magnetic surveys were conducted in a grid of 0.1 m × 0.1 m over the anomalous areas detected in the previous survey. Magnetic data were later corrected for daily variations by means of repeated measurements at a local base station and the continuous record at the nearest magnetic observatory.

At the Ermedàs site a Scintrex Envimag proton magnetometer was used to record the magnetic field intensity at each station. Its sensibility ranges from 0.1 to 1 nT. The sensor was placed 30 cm above the ground surface according to the expected dimensions and depth of the magnetic target. A second magnetometer was used as base station to account for temporal variations in the magnetic field. Readings were automatically logged at walking pace, allowing large amounts of data to be recorded and stored quite rapidly. The survey was undertaken within grids at a 1 m traverse separation, totalling 10,000 readings per hectare. Computer processing of data in the field allowed the survey to be monitored and modified almost in real time.

Since magnetic signals associated with archaeological features are very small and easily masked by trash metals, power lines, metallic fences, nearby automobiles, etc., an ocular inspection at both sites and previous tests were performed before conducting the complete survey.

4. Magnetic data processing

After the diurnal variation correction has been performed, the magnetic data requires all the other causes of magnetic variation from the observations other than those arising from the magnetic effects of the subsurface be removed. These reductions are mainly: elevation and terrain corrections and main field reduction.

Elevation and terrain corrections were omitted because both studied sites are flat enough to consider these effects negligible. On the other hand, the main field can be mathematically evaluated from the model derived by the International Geomagnetic Reference Field (IGRF) or the MAGSAT Earth-orbiting satellite, but an alternative method of removing the regional trend over a relatively small survey area is by the use of trend analysis. The latitude correction was found to be less than 5 nT per kilometre. Then, in our case, a first order surface, fitted by applying the least squares criterion to the non-anomalous measurements, was subsequently subtracted from the observed data to leave the local anomalies.

The magnetic survey detected significant anomalies on a piece of land situated east of the Plà d'Abella farmhouse. The distribution of the anomalies in this plot, after magnetic data were corrected for diurnal variations and the regional field removed, is depicted in Fig. 2. Four intense dipolar anomalies and other low amplitude dispersed ones are evident. Immediately after the location of the main anomalies, a new survey was performed with a sampling grid of 0.1 m. Fig. 3a shows one of the detailed residual magnetic maps depicting a typical dipolar anomaly.

After the survey was over, great importance was given to the way in which data are enhanced. The well known image-processing algorithms, if correctly applied, are able to reveal, in detail, the presence of anomalies otherwise difficult to identify. In the last two decades, Linington (1970) and Scollar et al. (1986) introduced many innovations for the presentation and interpretation of magnetic data, for instance. Of particular interest are reduction-to-the-pole and horizontal gradient transforms.

The asymmetry of the magnetic anomalies can be compensated by the method of reduction-to-the-pole. This consists of recalculating the observed anomaly for the case that the magnetization is vertical (Baranov and Naudy, 1964). The Fourier transform of the matrix was

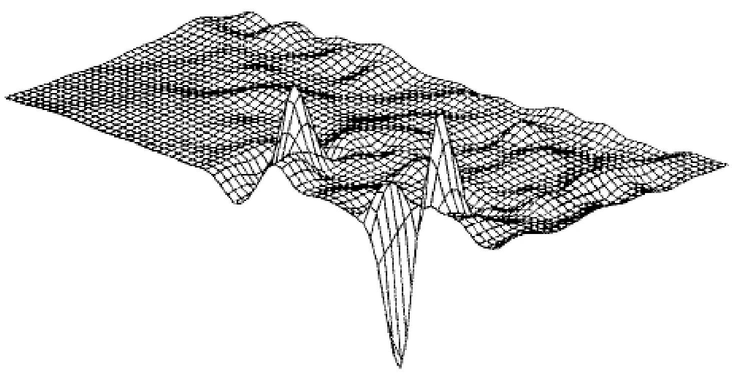

Fig. 2 - Dipolar magnetic anomalies located on a plot of land close to the Plà d'Abella farmhouse from the 1 × 1 m grid survey.

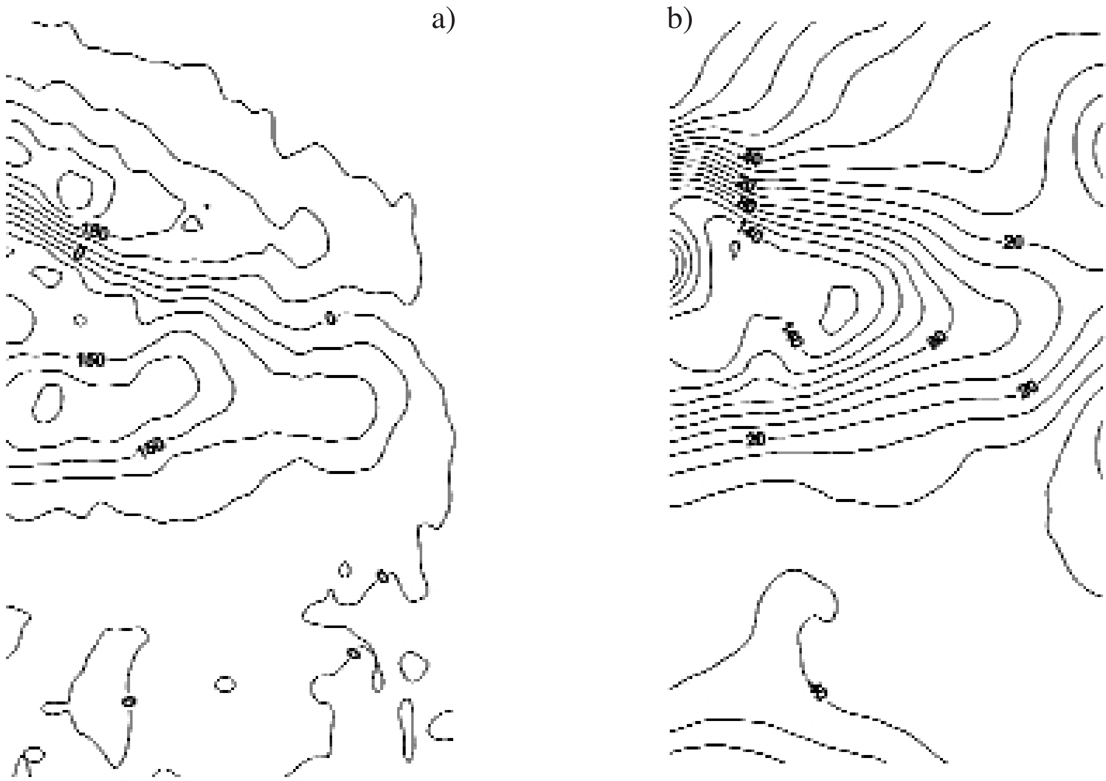

Fig. 3 - a) Detailed residual magnetic map of the first detected kiln depicting a typical dipolar anomaly. Contour interval is 50 nT. b) Detailed reduced-to-the-pole magnetic map of the first detected kiln depicting a monopolar anomaly over its apparent source. Contour interval is 20 nT.

computed and convolved with a filter function to correct for the orientations of the body and its magnetization. This filter is a mathematical process to minimize or eliminate the asymmetry and lateral displacement of the magnetic anomaly with respect to the main axis of the causative body.

The Fourier transform of the observed magnetic field $T\ (u,v)$ and its transformed field $T'(u,v)$ can be related as,

$$T'\ (u,v) = \frac{M'_o\ (u,v) \cdot M'_m\ (u,v)}{M_o\ (u,v) \cdot M_m\ (u,v)} \cdot T\ (u,v), \tag{1}$$

where $M_o\ (u,v)$ and $M'_m\ (u,v)$ are functions that depend on the geometry and polarization field vectors defined as,

$$M_m\ (u,v) = iul + ivm + (u^2 + v^2)^{1/2}\, n, \tag{2}$$

$$M_o\ (u,v) = iuL + ivM + (u^2 + v^2)^{1/2}\, N, \tag{3}$$

(L, M, N) and (l, m, n) are the direction cosines in the direction of magnetization (ambient and remanent fields).

The former expression can be rewritten as a spectral transformation of the direction of the magnetization in terms of the reduced field as,

$$T'(u,v) = \frac{(u^2 + v^2)}{\left[iuL + ivM + (u^2 + v^2)^{1/2}\right]\left[iul + ivm + (u^2 + v^2)^{1/2}\right]} T(u,v). \quad (4)$$

Taking into account that the magnetization is mainly of thermoremanent origin, the declination and vertical inclination for magnetization and ambient field at the time of the last cooling was derived by Parés et al. (1992) on a Roman kiln of the same period. They found that, on average, the inclination and declination angles were 59 ° and 2.6 °, respectively. On Fig. 3b the detailed reduced-to-the-pole magnetic map of the first detected kiln depicts a monopolar anomaly over its apparent source with intensity up to 140 nT and steep gradients on both sides. This anomaly was interpreted as having been produced by one of the searched kilns, therefore, the excavation was conducted vertically revealing a kiln at an approximate depth of 35 cm. Fig. 4a displays a view of the first kiln detected. A detailed map of each fired clay refractory block from the kiln walls was made using the same grid reference used in the magnetic survey. Figs. 4b and 4c show the residual magnetic map and the reduced-to-the-pole map respectively, overimposed on the structure of the kiln. The comparison between both images clearly explains how the reduction-to-the-pole transform has improved the precise location of the kiln.

At the Ermedàs site, different significant and definite dipolar anomalies were clearly depicted on the residual magnetic anomaly map. One of the biggest anomalous area is labelled with an A on Fig. 5 and could be interpreted as a huge deposit with broken or fault pottery because randomly oriented material gives generally high positive readings, but without any clear dipolar pattern. The number and extension of the anomalous zones supports the strong suspicion

a) b)

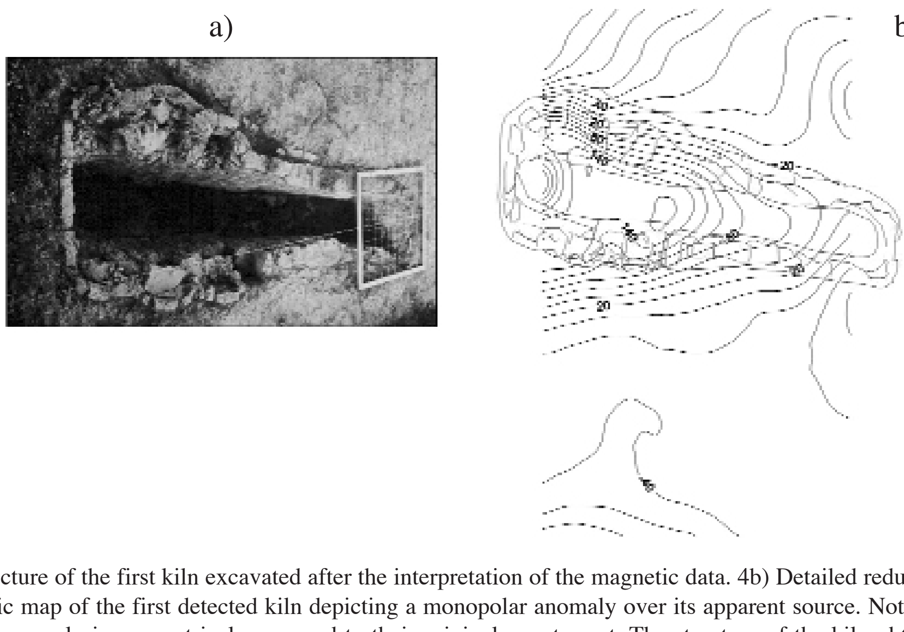

Fig. 4 - a) Picture of the first kiln excavated after the interpretation of the magnetic data. 4b) Detailed reduced-to-the-pole magnetic map of the first detected kiln depicting a monopolar anomaly over its apparent source. Notice that the transformed anomaly is symmetrical compared to their original counterpart. The structure of the kiln obtained after digging is over-imposed to the magnetic contour map. Contour interval is 20 nT.

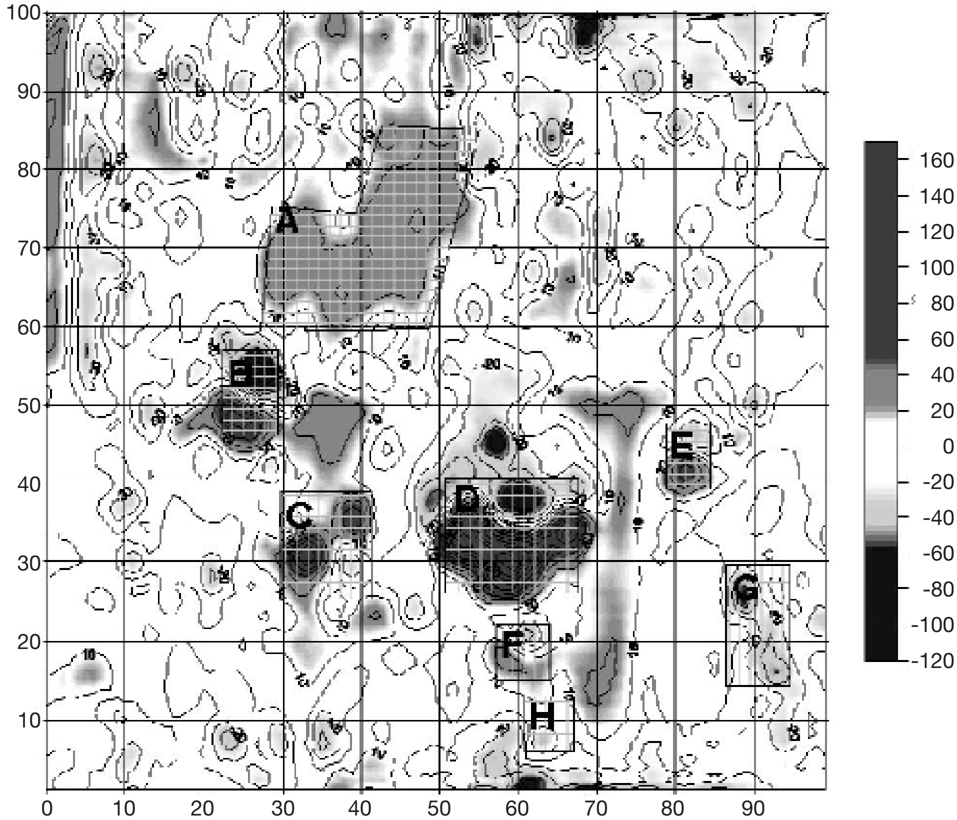

Fig. 5 - Magnetic anomalies derived from the 1 × 1 m survey at the Errmedàs site. Contouring interval is 10 nT. Dashed areas are those suggested for primary archaeological excavation.

that this was an important industrial centre and thus their study should answer some of the questions concerning Roman pottery production centres in ancient Hispania. The most prominent anomaly is a three-lobular one placed almost at the centre in the studied area and labelled with a D on Fig. 5. Until now only this area has been excavated, giving eight adjacent kilns of rectangular shape, the biggest having a side of 4.5 m. The anomaly shows a complex pattern because of a superposition of magnetized structures and the rectangular shape of the remnants of the kiln is not well recorded. Nevertheless, by comparison with excavation results there is a good correspondence between excavated structures and the magnetic anomalies as can be deduced from Fig. 6.

The information related to the boundary of the sources may be enhanced by calculating the horizontal gradient (Blakely, 1996). The steepest horizontal gradient of a reduced to the pole magnetic anomaly tends to overlie the edges of the causative body. We can exploit this characteristic in order to locate abrupt changes in magnetization. The magnitude of the horizontal gradient is easily calculated by

$$H(x,y) = \left[\left(\frac{\partial T(x,y)}{\partial x} \right)^2 + \left(\frac{\partial T(x,y)}{\partial y} \right)^2 \right]. \quad (5)$$

Fig. 6 - Picture of the Ermedàs Roman pottery kilns after the archaeological excavation.

The final step of boundary analysis concerns recognizing the maxima of the horizontal field derivative. Applying the shaded relief method can facilitate this operation. Fig. 7 depicts the result obtained after the shadow relief method has been applied to the anomaly labelled E on Fig. 5.

5. Soil magnetic properties

The knowledge of magnetic soil properties is essential to decide if a site is suitable to be surveyed by magnetic method or not. Typically, soils that have had a campfire maintained over them develop an increased magnetic susceptibility resulting from the consequent reducing environment. This reducing environment causes the formation of magnetite if even moderate amounts of iron are present. On the other hand, soils compacted by human occupation or disturbed by a burial will also show a variation from background values of magnetic susceptibility. Burials frequently cause localized oxidation, creating a void in magnetite content.

Agricultural soils in the studied zones are mainly ochrepts generated from limestones and sandstones of Eocene-Oligocene age. Graham and Scollar (1976) have shown that soils are magnetically roughly uniform, in spite of the pedological differences from place to place, depending on the parent rocks, local topography, climate and plant growth history. To analyse the magnetic properties of the soils almost a half-kilogram of soil sample was taken at every sampling place and transported to the laboratory for drying and mechanical preparation. In order to remove any large piece of pottery or brick, soils were sieved using a standard 2 mm brass sieve. The magnetic susceptibility was measured directly over the surface of the sample by a kappame-

Fig. 7 - Effect of data processing by horizontal gradient transform on an isolated magnetic anomaly. The shaded relief representation of the reduced-to-the-pole anomaly labelled E on Fig. 5 allows us to recognize the lateral edges of the structure that generates the magnetic anomaly.

ter KLY-2 from Geofyzika Brno, giving values in the range between 2.8×10^{-5} and 5.8×10^{-5} SI.

At the Ermedàs site samples from the walls of the kilns and ceramic material found during the excavation were collected and cut into standard cylindrical specimens for routine magnetic analysis in the laboratory. The remanence of the clay-fired specimens was investigated in detail by means of thermal as well as alternating-field (AF) demagnetisation. A thermal and an AC tumbling demagnetizer (Schonstedt Instrument Co.) was used and temperatures/fields of up to 700 °C/100 mT were reached. The diagrams on Fig. 8 corresponding to the demagnetisation, either thermal or alternating field, show that two phases are present: a first with temperatures

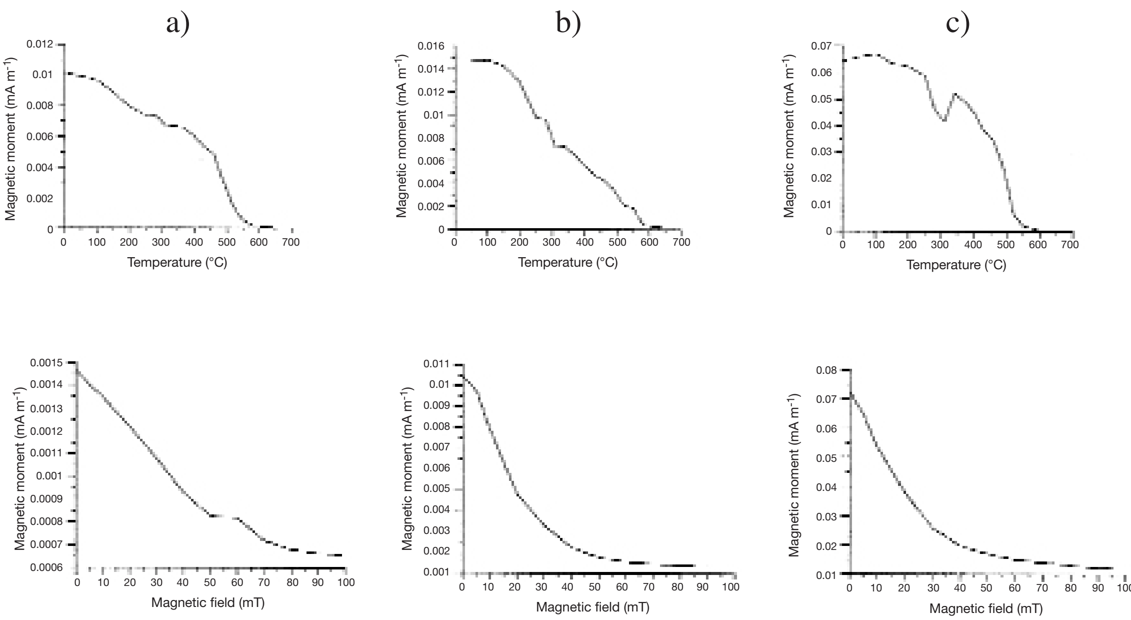

Fig. 8 - Thermal (up) and alternating field (down) demagnetisation of three characteristic samples from the Ermedàs site: a) brick from kiln wall, b) *tegulae* and c) *amphorae*.

close to 300 °C and a second one with temperatures between 490 ° and 580 °C. The first one could be due to the presence of iron sulphides that have a de-blocking temperature around 350 °C. All specimens have Curie-points around 580 °C, indicating the dominant magnetic carrier to be pure magnetite, which is also supported by the bell-shaped decay-curve of the AF demagnetisation, being around 40 mT the median destructive field. On the *tegulae* and *amphorae* samples some signal up to 650 °C still remains suggesting a minor contribution from haematite particles with a higher coercivity.

Fig. 9 shows the evolution of the magnetic susceptibility of the same three samples when temperature increases. Susceptibility values are very different, the *amphorae* having the highest value and the kiln's wall the lowest. This fact can be interpreted more as a grain effect than differences in magnetic components.

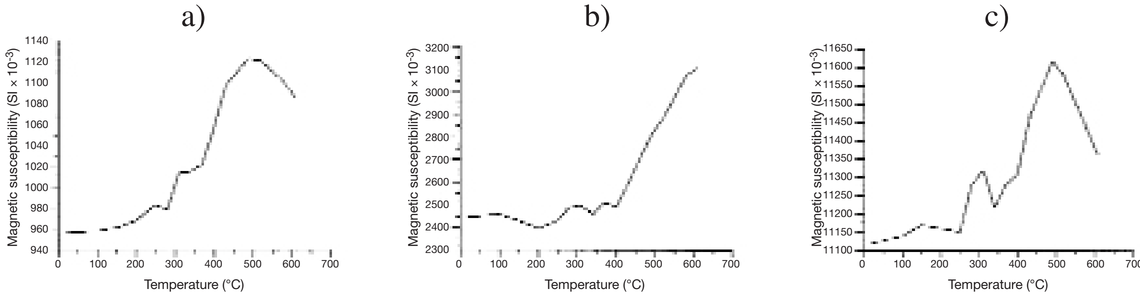

Fig. 9 - Evolution of magnetic susceptibility with temperature. Samples coming from the Ermedàs site: a) brick from kiln wall, b) *tegulae* and c) *amphorae*.

6. Comments and conclusions

Heritage safeguarding of sites having archaeological interest, like Roman pottery kilns can be performed by precise location through magnetic exploration. The method has been largely improved for this particular application during recent years through the development in the techniques of data acquisition, processing and interpretation.

Magnetic surveys presented in this paper have shown the usefulness of the method for detecting and mapping archaeological structures like kilns, fired clay pottery dumps and other thermoremanent magnetized objects. Among the different techniques that can be applied to the magnetic data, reduction-to-the- pole and horizontal gradient transformation have revealed their efficacy in delineating the precise position of shallow depth magnetic anomalous bodies. In this way, the archaeologist can select digging priorities based on survey findings and the sites could be preserved from salvage prowling. Also, based on the geophysical evidence, substantial funding for archaeological research prior to the clearing of an area and construction of new roads or buildings may be available.

At the Plà d'Abella site, four kilns were easily detected by the magnetic method. Furthermore, the reduction-to-the-pole transform removed the asymmetry of the dipolar anomalies, allowed a better location and definition of their shape. At the Ermedàs site eight kilns were detected, revealing the existence of an important industrial centre, but some magnetic anomalies have not been excavated yet.

The magnetic analysis of natural soils and samples has demonstrated their interest as a complement of the magnetic survey, giving information about their response to thermoremanent magnetization and origin.

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