MINERAL-MAGNETIC CHARACTERIZATION AS A KEY TO EXPLAIN DIFFERENCES IN MAGNETIC CONTRAST AND IMPROVE ARCHAEOLOGICAL INTERPRETATION

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Mineral-Magnetic Characterization as a Key to Explain Differences in Magnetic Contrast and Improve Archaeological Interpretation

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Ekhine Garcia-Garcia [a], Hana Grison [b], Neli Jordanova [c], Philippe De Smedt [d] and Eneko Iriarte [e]

Highlights:

- *New approach to mineral-magnetic characterization.*
- *Evaluation of factors influencing geophysical results.*
- *Origin of a fringe without magnetic contrast explained by waterlogging.*

Keywords: archaeological geophysics, Roman site, magnetic contrast, mineral-magnetic characterization, moisture.

Introduction

Geophysical and geoarchaeological methods can be used to delimit the extent and characterise the nature of settlement in the past. To this end, a magnetic survey was conducted at the site of the ancient Roman town of Zaldua (Auritz, Navarre). Although the results of this survey provided a firm basis for a preliminary archaeological assessment of the site (Garcia-Garcia *et al.*, 2016), in some parts of the study area the magnetic response was difficult to interpret. This is most striking in the north of the main area, where a narrow band without clear magnetic variation separates two zones with clear evidence of intensive occupation. The same result was reproduced in the Ground Penetrating Radar (GPR) and Electromagnetic Induction (EMI) surveys performed in this area. The absence of clear responses is believed not to reflect archaeological reality but the reason for this contrast-free fringe is unknown, and remains one of the archaeological questions of the site.

A Short Time Scientific Mission (STSM), conducted as part of the ongoing COST Action 17131 – SAGA program, brought together specialists from the fields of geophysics, archaeology, environmental magnetism and soil science from four countries with the main aim to improve *in situ* measurements using soil magnetic characteristics to understand the factors affecting geophysical results, in order to better interpret archaeological features. The presentation here showcases the investigations focused on the fringe area described above. The objective was to compare the magnetic properties of the fringe with those of settled areas, the

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expectation being that it could help to establish the origin of the fringe and lead to an understanding of why there are no archaeological remains present in this area.

Site description and methodology

The extensive remains of the ancient Roman city of Zaldua in the north of the Iberian Peninsula, functioning from the 1st century AD to its abandonment in the 4^{th} century AD, was discovered in 2012 and geophysical methods have been used extensively to delimit and characterise the settlement (Garcia-Garcia *et al.*, 2017). Archaeological excavations have been ongoing annually since 2015 and the partial results have been compared to the results of previous geophysical investigations. The main area of about 4.5 ha has been shown to be densely occupied and separated from a small secondary area (0.45 ha) by a narrow fringe devoid of a clear magnetic contrast (Fig. 1).

The study was performed on a set of samples from 13 cores, 1-2 m long, drilled with a handheld coring machine. The samples were made from 1 to 10 cm thick sections, predetermined by the archaeologically identified stratigraphic layers. Laboratory measurements were done at the Institute of Geophysics of the Czech Academy of Science, Prague, Czech Republic.

For all samples, magnetic susceptibility (MS) was measured at low (976 Hz) and high frequency (15616 Hz), using Kappabridge MFK1-FA (AGICO, Brno, Czech Republic). Frequency-dependent magnetic susceptibility (χFD) was calculated as a relative and absolute change of MS obtained for low and high frequencies. This approach allows the relative content of pedogenic superparamagnetic (SP) grains and discriminating potential archaeological layers to be estimated (e.g., Dearing, 1996; Fassbinder, 2015; Hrouda, 2011). Bi-plots of the MS and χFD permitted a comparison of the relations between different magnetic contributions in the investigated cores.

In order to identify magnetic grain size and mineral composition, the hysteresis and remanence characteristics were determined using a Vibrating-sample magnetometer (ADE Corporation, VSM EV9 VSM 2900). The measurement cycle was composed of the hysteresis loop, acquisition of the Isothermal Remanent Magnetization Curve (IRM) and the DC demagnetisation remanence curve (DCD). Data were subsequently evaluated in a Day plot (Day *et al.*, 1977).

Results

Data from the MS measurement of cores and geophysical data, gradiometric and EMI, are very consistent (Fig. 2). Cores located in the area with no magnetic contrast show the lowest MS values (cores 16, 20 and 21; average value of 16×10^{-8} m^3/kg). The exceptionally high values of MS in some samples (178×10^{-8} m^3/kg) can be related to small inclusions of slag or pottery. Cores located in areas with high magnetic contrast show the highest MS values (P1004, P1006, P27). In most cases, increased MS values (range of $324–2026 \times 10^{-8}$ m^3/kg) correspond to the results obtained for samples from the archaeological deposits. The rest of the investigated cores show "intermediate" MS values (in the range of $7–270 \times 10^{-8}$ m^3/kg, average 57×10^{-8} m^3/kg). The bi-plot of the absolute change of χFD and MS shows that the bulk of cores from the area follows the same magneto-mineralogical trend (Fig. 2b). This is interpreted as representing similar pedogenic processes going on throughout this area (Evans & Heller, 2003; Jordanova, 2016). The excep-

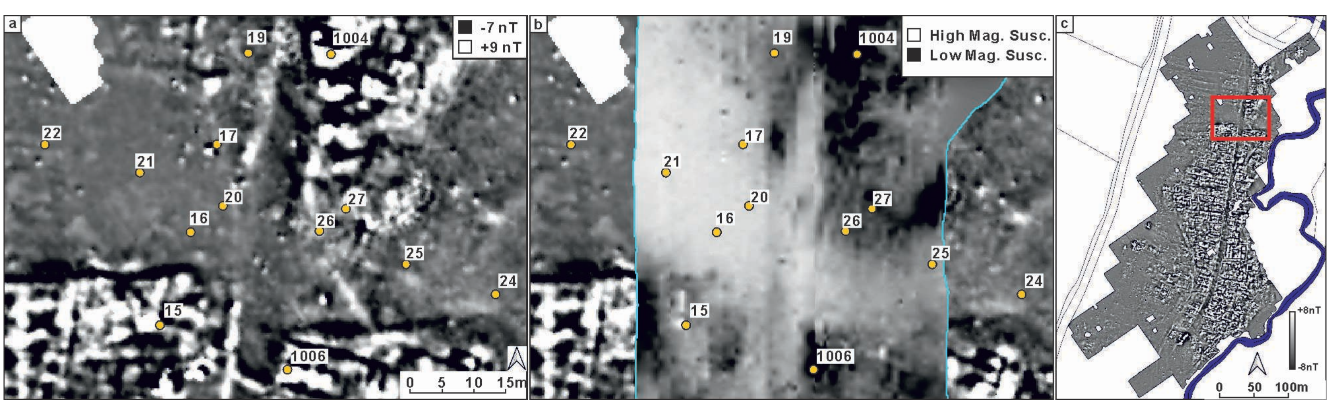

Figure 1. The gradiometer response map (-7 nT black, +9 nT white) and the magnetic susceptibility map from the EMI survey (in-phase HCP response, highest positive sensitivity 0–0.5 m), with core positions indicated. The location of the fringe zone is marked on a general map of the settlement.

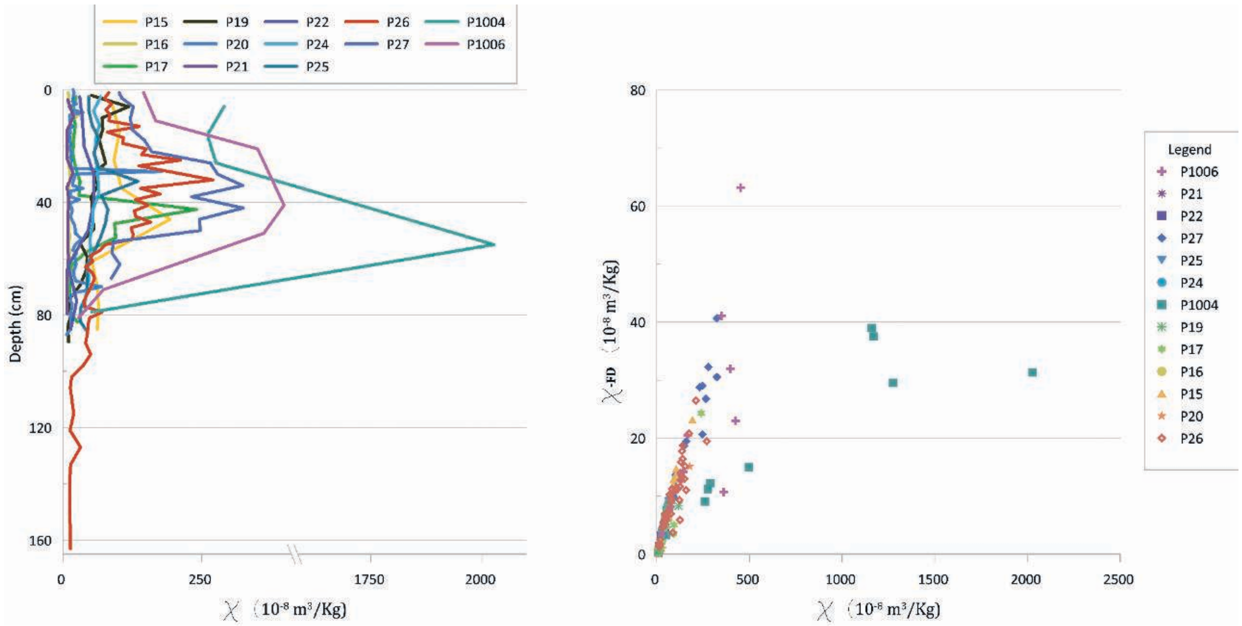

Figure 2. (a) Vertical distribution of magnetic susceptibility along cores from Area 2 (horizontal axis broken); (b) bi-plot of the absolute change of frequency dependence and mass magnetic susceptibility.

tion is core P1004, which has a notably lower SP fraction indicating a different origin of the magnetic minerals.

The Day plot in Figure 3 summarizes magnetic grain size of selected samples in cores P15, P16, P27, P1004 and P1006. The hysteresis curves were corrected for the paramagnetic part by subtracting the linear part of the loop from the whole signal. Core P16, positioned in a poorly magnetic area, shows a mixture of different minerals. The hysteresis curve of P16-38, for instance, is not closed, indicating that it is influenced by a high coercivity mineral, such as goethite. Sample P16-04 is located in the topsoil horizon and shows large, multidomain magnetic grain size, most probably of anthropogenic origin (modern pollution). Samples of the "strongly magnetic" core P1004 are located in the pseudo-single domain (PSD) area; therefore, only one dominant mineral type is expected (Dunlop, 2002).

Discussion and conclusions

Analysis of the mineral magnetic characterization of the samples leads to the conclusion that the provenance of magnetic minerals is similar for all of the cores. Indeed, they show a similar frequency dependence of magnetic susceptibility, suggesting similar pedogenic influence. Therefore, an external contribution of magnetic minerals should be discarded, and areas without magnetic contrast correspond to areas where the pedogenesis did not result in significant magnetic enhancement. Core P1004 is different. Here, an external contribution of magnetic minerals should be considered. Indeed, the gradiometer response map indicates thermally enhanced areas, which could indicate industrial activity.

However, the hysteresis parameters show a notable difference in core P16, located inside the fringe without magnetic contrast. The high-coercivity component combined with low magnetic susceptibility suggest the existence of a mixture of magnetic minerals with different coercivities (Maxbauer, 2017). By contrast, the presence of a single dominant magnetic mineral is to be expected in the other cores.

Waterlogging in the fringe could be considered as an explanation for these observations. It would create an environment, in which iron (hydro)oxides could be transformed into hard-coercivity goethite instead of magnetite (Cornell & Schwertmann, 2003). From an archaeological point of view, a higher water table level would explain why there are no construction remains in the fringe. Therefore, the preliminary conclusion in this case is that the fringe reflects inconvenient terrain rather than an intentional marking of a separation between two areas of occupation.

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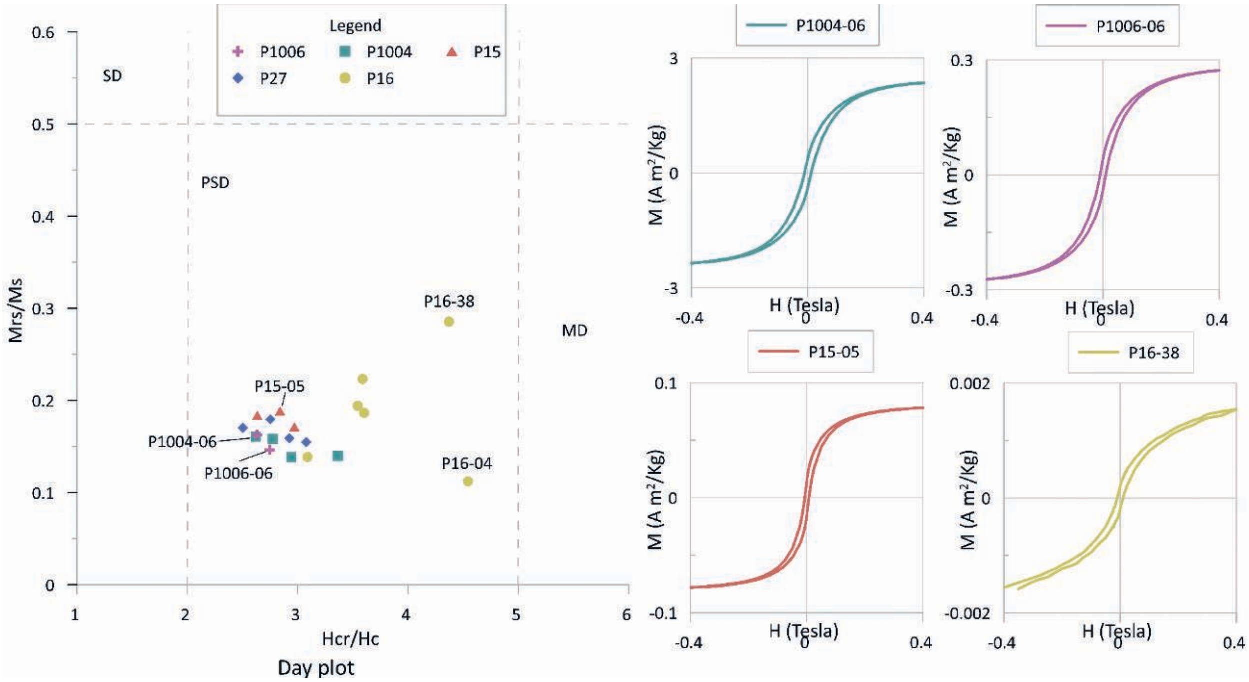

Figure 3. Day-plot and hysteresis loops of selected samples from Area 2 (vertical scale adapted to each loop).

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