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Comparison of geophysical prospecting and geochemical prospecting at the Medieval and Modern Cistercian Abbey of Carnoët (Finistère, France)

Arthur Laenger, Centre de Recherche en Archéologie, Archéoscience, Histoire (UMR CNRS 6566 CReAAH), Le Mans Université

Address: Département Histoire, Avenue Olivier Messiaen, 72085 Le Mans France

Phone: 06 75 93 07 01

Email: Arthur.laenger@univ-lemans.fr

Arnaud Martel, Institut des Matériaux et Molécules du Mans (UMR CNRS 6283 IMMM), Le Mans Université

Fabien Boucher, Institut Universitaire de Technologie du Mans département chimie, Le Mans Université

Xavier François, Géocarta

Michel Dabas, Archéologie et Philologie d'Orient et d'Occident (UMR CNRS 8546 AOROC), Ecole Normale Supérieure, Paris

Joséphine Rouillard, Centre de Recherche en Archéologie, Archéoscience, Histoire (UMR CNRS 6566 CReAAH), Le Mans Université

Aline Durand, Centre de Recherche en Archéologie, Archéoscience, Histoire (UMR CNRS 6566 CReAAH), Le Mans Université

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Abstract

Saint-Maurice Abbey in Carnoët (Finistère) underwent an in-depth archaeological appraisal during 2018-2019, involving several non-destructive technologies: the geophysical survey revealed the presence of expected structures, drawn on ancient plans, but also the presence of structures unknown up until now. A group of buildings on the edge of the pond in particular raised several questions. A geochemical survey was carried out there in order to try to characterise these buildings and observe the potential complementarity between geophysical and geochemical surveys. The results of the chemical analysis do not highlight the same level of detail of the structures as electrical resistivity, but these analyses seem to be able to clarify the geophysical diagnosis by discriminating signals of structures from echoes linked to the geological substrate.

1) Introduction

The chemical analysis of soils, through the dosing of phosphates, is an internationally used technique in archaeology since the 1930s (Arrhenius 1931, Arrhenius 1934), and has been applied by French archaeologists since the 1950s (Louis 1946). Even today, it is systematically conducted to identify livestock-related structures, by establishing the link between phosphorus deposits and animal excrements (Craddock et al. 1985). However, the technique was extended to other chemical elements as early as the 1970s in Mexico (Barba & Bello 1978) in order to characterise anthropogenic activities on a wider scale. The analytical methods described at the time may seem inadequate to the contemporary chemist, but they have been constantly developed and experimented with over the past decades (Middleton et al. 2010, Dirix et al. 2013). The latest improvement is the replacement of

inductively coupled plasma analytical techniques (ICP-MS, ICP-AES, ICP-OES) with X-ray fluorescence spectrometry (XRF). Although this analytical technique only yields semi-quantitative results compared to ICP, these results are sufficient for the context of soil analysis for archaeological purposes based on variations in concentrations. Furthermore, comparative studies have shown a good correlation between results obtained by traditional techniques and XRF analysis (Frahm et al. 2016). In most cases, a field device is used, with minimal sample preparation (Rippon, Martin & Jackson 2001, Wilson, Davidson & Cresser 2008, Wilkins 2009, Hayes 2013, Hafez et al. 2017, Smejda, Hejcman & Horak 2017, Cannell et al. 2018, Gutiérrez-Rodríguez et al. 2019, Save et al. 2020). One of the advantages of XRF is that it is easier to carry out analyses, as sample preparation is limited to drying and grinding instead of the acid digestion required for ICP. Another advantage of XRF is that all but a few chemical elements can be studied in a single analysis. However, above all, XRF presents huge prospecting potential as the broad spectrum of scanned elements can highlight significant differences in the concentration of elements not yet considered interpretable, paving the way for the identification of new markers of anthropogenic activity. In addition, since all of these data are recorded for each studied site, it is possible to return to sites retrospectively, once a marker has been clearly identified at another site.

As concentrations of chemical elements in soils are intricately linked to the geological environment, it is not so much a question of establishing target concentration values to distinguish an activity, but rather of identifying distribution anomalies in soils. This can be accomplished by establishing variations in elemental concentrations, which are available from semi-quantitative data. The aim of the study is to investigate the possibilities of combining geophysical prospecting, well known and often used by archaeologists, with geochemical prospecting (Tabbagh et al. 2000, Wiseman & El-Baz 2007, Gaffney 2008, Deiana, Leucci & Martorana 2018). Although experiments have already been carried out outside France (Persson 2005, Campana et al. 2009, Nolan & Redmond 2015, Cardarelli et al. 2016, Conger & Birch 2019, Cuenca-García 2019), to our knowledge this is the first application of this procedure on French soil. The Cistercian abbey of Saint-Maurice de Carnoët is a test site where both techniques were implemented in joint operations.

2) Context of the study site

Saint-Maurice de Carnoët Abbey is located to the east of the commune of Clohars-Carnoët in Finistère. The geological context of the abbey is characteristic of the Morbihan; metamorphic complexes of the South Armorican Variscan domain, composed of Moëlan orthogneiss, Ordovician orthogneiss and Augen orthogneiss with locally migmatitic biotite. Near the Laïta River and the water bodies, we also observe the Nerly group, from the Pouldu unit, composed of often bedded micaceous leucocratic paragneiss (Chauris 2013).

It is one of thirteen Breton Cistercian abbeys located on a wooded hill near the bank of the Laïta River. The Ster Nadred stream was transformed into a pond, south of the abbey. The monastic complex was founded in 1170 and remained in the possession of the order until 1789, when it was sold as national property. Over time, the small rocky hill on which the abbey was built was transformed into terraces in order to meet the needs of the monastic community. It subsequently passed from hand to hand, was occupied by the German army during the Second World War, and was finally bought by the Conservatoire du Littoral (National Institution in charge of land policy to safeguard the coastal area) in 1991. The remains of the abbey are sparse, but the institution has begun restoration work and the orangery, the farmhouse and the abbey dwelling, the barn and chapter hall have now been restored. A joint geophysical and geochemical survey was undertaken as part of a general study of the site carried out in 2018 under the direction of Joséphine Rouillard (Rouillard et al. 2019). The aim of this study is to assess the available documents, and carry out a technical preparation, prior to an archaeological excavation. The documentary assessment carried out by Joséphine Rouillard reveals that only rare and incomplete medieval and modern written sources exist for the abbey. Saint-Maurice is a modest-sized abbey, with a small number of monks. It was not specialised and practised polyculture. The

cultural and political influence of the abbey was very limited, as it only held a subordinate rank in the hierarchy of Breton Cistercian abbeys (Dufief 1997). The archaeological challenge is to study the conformity of the spatial organisation of the abbey of Saint-Maurice de Carnoët with the theoretical plan of the Cistercian order. It also intends to explore the underground hydraulic system, another speciality of the Cistercian order. Before beginning the excavation operation, the preliminary study can only be non-intrusive, as the site is classified as both a protected natural area and a historical monument. Geophysical prospection is particularly well suited to address these issues prior to excavation without causing any disturbance to the site. It was first used in May 2018 when it highlighted the layout of the abbey and revealed the internal hydraulic network (water supply and drainage). In addition, signals appeared in areas not covered by the old plans of the abbey. These areas were subsequently prospected during the complementary geochemical study, conducted in October 2019 and discussed in this article. In the end, the planned excavation operation never took place.

The aim was to check whether geochemical prospecting can provide additional and useful information to the archaeologist over and above that obtained by geophysical prospecting. In particular, the question is whether geochemical prospecting can be used to characterise archaeological structures. The rare known old plan of the abbey, dating from the eighteenth century (Rouillard et al. 2019, fig. 5 p. 243, fig. 6 p. 244) does not show a workshop for the maintenance of tools or a small forge. The mention of Cistercians and metallurgy immediately brings to mind large abbeys specialised in iron production (Benoit & Cailleaux 1991), but smaller abbeys were not necessarily dependent on the latter for their supply of materials. Smaller abbeys, such as Saint-Maurice, which were more focused on agriculture and animal husbandry, also needed to maintain tools. This would have been carried out in small workshops, as observed in other Cistercian abbeys (Blary 1989, Astill 2011, Rouzeau, et al. 2015, Blary 2021). One hypothesis is that such a building might be present in the area studied in this article. The results illustrate the complementarity of these two types of prospecting.

3) Materials and methods

3.1) Sampling

The sampling area covers 900 square metres on the edge of the western part of the abbey pond (Fig. 1). This area contains the features revealed by the geophysical survey (Fig. 2). Samples were taken from a quadrangular grid of two metres on each side, for a total of 256 samples. As the area is subject to a non-destructive archaeological survey permit, samples were taken using a gouge auger in the first sedimentary levels. It was not possible to excavate a test pit to check the stratigraphy. The first ten centimetres of soil, corresponding to the plant horizon, were removed with a hand hoe, and then samples were taken with the auger, on average from a depth of 15-20 cm in relation to the surface. It seems obvious that archaeological levels cannot be sampled with this sampling technique, as they lie at greater depths, but this does not contraindicate the implementation of a geochemical survey for archaeological purposes. In fact, the work of Cuenca-Garcia has shown that most of the concentrations of chemical elements interpreted in archaeology tend to be distributed vertically (Cuenca-Garcia 2013). It is thus possible to perceive deposits present deeper in the first levels. However, this effect entails a significant bias: the signal perceived on a surface point results from the addition of all the deposits of chemical elements beneath it, with no a priori possibility of discriminating them. However, this bias can be compensated for by focusing prospecting studies on structures that were abandoned after use and not subsequently reoccupied. This is the case for the hypothetical complex of buildings at the edge of the pond studied here.

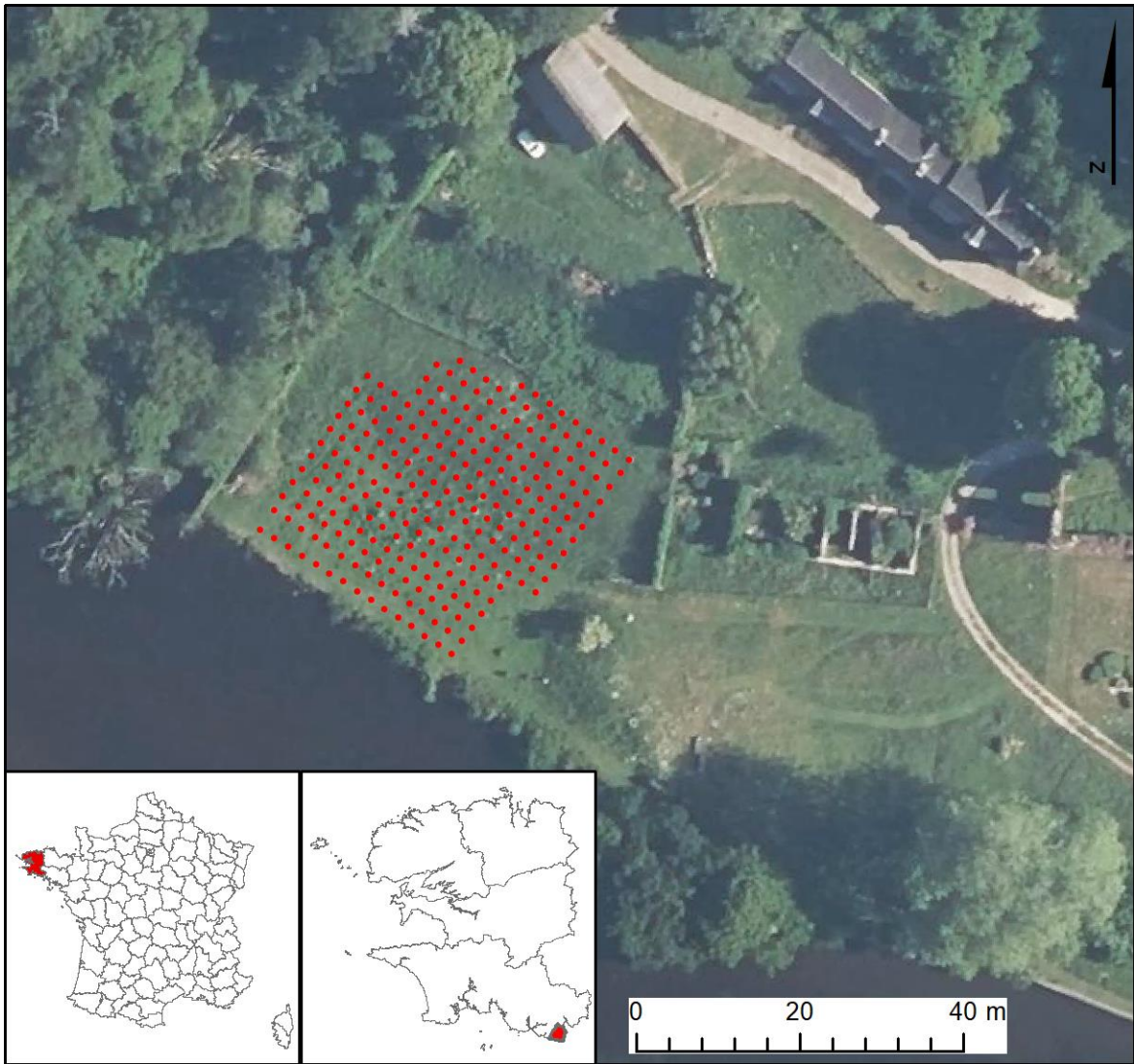


Fig. 1 – Location of the studied zone (Satellite image: Geoportail)

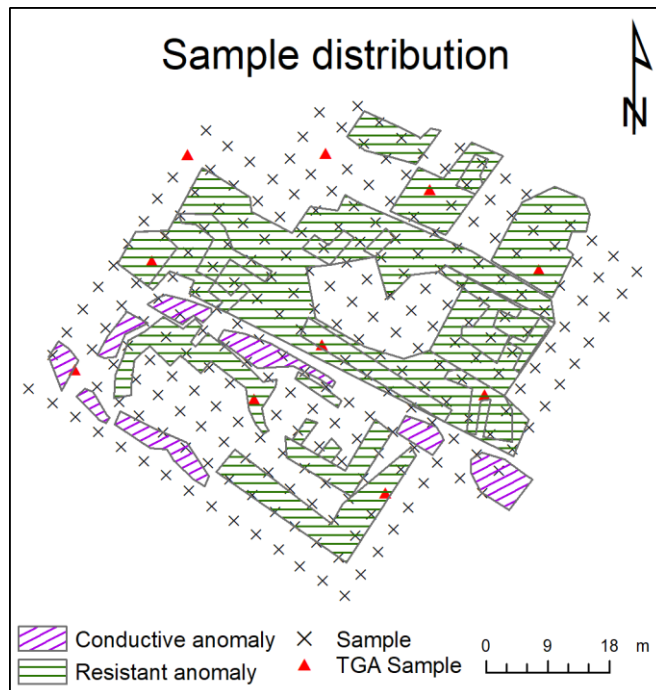


Fig. 2 – Position of samples in relation to the results of geophysical prospecting

3.2) Geophysical analysis

Geophysical surveying is a non-destructive subsurface mapping method often used in archaeology. It detects the location of potential archaeological remains, as well as their shape and orientation. This information is usually used to determine the location of archaeological excavations. The present campaign was carried out by the Géocarta company, which applied the Automatic Resistivity Profiler mapping method (ARP) (Dabas 2009). The principle of this technique is based on the measurement of the capacity of the soil to oppose the circulation of an electric current. The ARP system replaces the electrodes with spiked wheel-shaped dipoles placed on four axles. The first axle carries the dipole that injects the electric current into the soil. The next three axles carry the dipoles that measure the electrical potential difference. The spacing between each dipole electrode increases on each axle, respectively 0.5 m, 1 m and 2 m, so it is possible to investigate the soil at different depths. The current used is 5 mA. The recording of resistivity variations is almost continuous, with a measurement taken every 10 cm. The position of the device is recorded by a Trimble differential GPS with decimetric accuracy. It is thus possible to prospect a large area in a short period of time. The entire acquisition process at Saint-Maurice, extending over an area of 1.25 hectares, was carried out in a single day.

In this way, it is possible to distinguish between resistive anomalies, where the electric current flows with difficulty, and conductive anomaly, where conversely, the electric current flows easily. The interpretation of areas with resistance or conductivity standing out from the background is then carried out by the Géocarta company.

3.3) Instrument and methods for sample preparation, XRF, pH and, thermogravimetric analysis (TGA).

3.3.1) Sample preparation

Samples were oven-dried at 105°C for twelve hours. They were then ground using a Retsch RM100 mortar grinder made of sintered corundum. Once the sample is placed in the mortar, it is ground by pressure and friction, with a scraper in the device bringing the sample back to the pestle. The particle size of the powder obtained after grinding is less than 100 µm. The advantages of grinding for the study are twofold. The first is to homogenise the sample, the second is to obtain a sufficiently fine granulometry to ensure a good and reproducible surface profile for performing the best XRF measurements. Indeed, this technique is dependent on the surface condition and the density of the sample. The use of 100 µm powders achieves satisfactory accuracy and measurement repeatability.

3.3.2) XRF analysis, instrument and methods

The instrument used for XRF measurements is a benchtop Epsilon 4 from Malvern Panalytical, more sensitive for the analysis of light elements such as P and S than portable XRF. The device is equipped with a silver anode X-ray tube with maximum power of 10 W, 50 kV voltage and a 2 mA current. Signal detection is via an SDD10 HR detector with a resolution of 135 eV at 5.9 keV. The spectrometer can perform elemental analysis from F to Am (K lines can be detected from F to Sb, and for elements from Te to Am, the L lines are used for quantifications and identification). During an analysis routine, each sample is bombarded directly and through the instrument's primary filters, namely 300 µm and 500 µm copper, 50 µm and 200 µm aluminium, 7 µm titanium and 100 µm silver. Using these filters makes it possible to concentrate the analysis on one part of the spectrum, limiting masking effects. In addition, the use of a helium stream is conducive to observing light elements with greater sensitivity. Measurements are performed using the Omnic method, the manufacturer's standardless semi-quantitative analysis software that automatically scans six conditions with different voltage, filter and current. The Omnic method was calibrated on delivery of the spectrometer and the gain is adjusted automatically with a Cu/Al alloy copper plate every twelve hours on Cu $K_{\alpha,\beta}$. The energy is calibrated on Al K_{α} and Cu $K_{\alpha,\beta}$. The measurements of the light elements are carried out under a helium flow according to the Omnic method and the sample spinner is activated. The measurements are taken in sample holders with an internal diameter of 30 mm, fitted with 6 µm mylar films in the form of loose powder. The Omnic method has been adjusted by the introduction of a tag

in Omnian calibration from a soil standard (Light Sandy Soil 1, Certified reference material, BCR-142R). The processing parameters used for our samples are as follows: Loose, Powder, Film correction: Mylar 6 μ m, Drift correction, Compound list: Geology, Normalization required to 100%, Compton Intensity. The compound list Geology displays the most abundant elements as oxides (P: P₂O₅, S: SO₃, Al: Al₂O₃, Si: SiO₂, Na: Na₂O, K: K₂O, Mg: MgO, Ca: CaO, Fe: Fe₂O₃). One of the main advantages of XRF is to provide concentrations of most chemical elements directly on solid samples. However, EDXRF is unable to quantify the elements below F. This drawback is addressed by the Omnian software, which issues an evaluation of the latter to calculate the content of the analysed chemical elements. In order to reduce this randomness and make the results more reliable, by bringing the semi-quantitative results even closer to the quantitative value, Omnian can integrate the measurement of some elements into the processing parameters. Carbon dioxide (CO₂), organic matter (CHON) and water (H₂O) concentrations were then measured by thermogravimetric analysis (TGA) on a set of 12 samples spread over the sampling area (see supporting information). The mean values from these samples were then integrated to the Omnian processing parameters. Although an EDXRF semi-quantitative method is not as accurate in absolute techniques as traditional analysis techniques such as ICP, the results obtained display good repeatability and provide the most important data for this study, i.e., concentration variations depending on sampling coordinates. In order to focus our study on the variations, data were normalized between 0 and 1, 0 standing for the lowest value and 1 standing for the highest value.

3.3.3) TGA analysis, instrument and methods

As previously mentioned, in order to obtain the closest values as possible to the actual elemental contents of the samples, the contents of water (H₂O), organic matter (CHON) and carbon dioxide (CO₂) made up of light elements (C, H, N and O) were measured by thermogravimetric analysis (TGA) on 12 representative samples. The samples were exposed to the following temperature program using a Mettler Toledo brand TGA2 thermogravimetric analyser: gradient from 30°C to 150°C at 10K/min, followed by a 15 min stage at 150 ° C, next a new gradient from 150°C to 800°C at 20K/min, then a new gradient from 800°C for the decomposition of carbonates, followed by a 10 min stage at 1000°C. These measures are close to loss-on-ignition measurements. At 150°C, water evaporates, then from 150°C to 800°C, organic matter pyrolyzes and decomposes, while above 800°C, the carbonates decompose. In this way, the amount of each compound (residual water, organic matter or CO₂ present in the samples) can be obtained by determining the respective mass gaps. An average of the values was then established, then these averages were integrated into the Omnian processing method (see supporting information).

3.3.4) pH analysis, instrument and methods

Finally, pH measurements were carried out in accordance with ISO 10390:2005(E) using a Metrohm pH Lab 827 pH meter, equipped with a 6.0228.010 probe.

3.4) Analysis of geochemical data

Not all the elements of the periodic table are represented. We only illustrate the elements present in sufficient quantities to exceed the quantitation limit of the instrument. In addition, we made a selection among the quantified elements, based on the presence of significant variations in concentrations. Variations in concentrations are shown according to the normalisation presented in 3.3.2. Values in ppm are given as an indication. Semi-quantitative analysis does not yield exact quantitative values, but it provides a very consistent order of magnitude.

Data from the analyses are integrated with archaeological data using a geographic information system (GIS), ArcMap from ArcGis version 10.7.1. This software caters for the management of spatial data, among others. In order to facilitate the reading of analysis results, we performed a spatial interpolation of data, transforming discrete data into continuous data. The most relevant interpolation method for

our dataset is inverse distance weighting (IDW). This method is particularly effective when data are dense and evenly distributed in space. By superimposing the maps obtained on the archaeological data, such as the orthophotographs obtained by photogrammetry or the plans, it becomes possible to propose interpretations.

4) Results

The complete results of the geophysical prospecting appear in a previous general publication (Rouillard et al. 2019 fig. 23 p. 256). A group of conductive and resistance irregularities, located west of the cloister, particularly attracted our attention (Fig. 3). As no building was reported at this location in ancient documentation, we decided to carry out chemical prospecting on the highlighted anomalies, in order to evaluate the benefit of combining the two prospecting techniques.

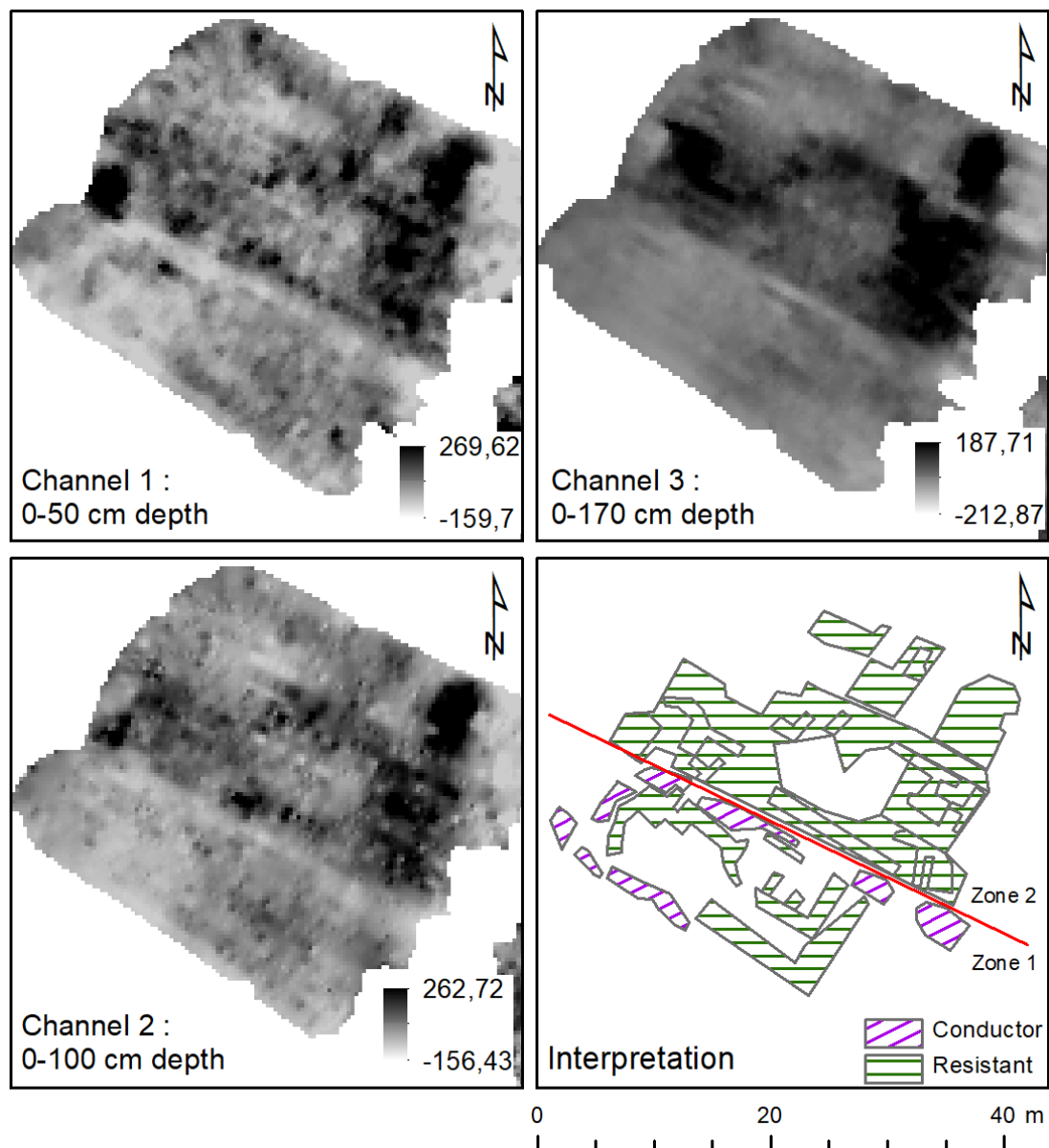


Fig. 3 – High-pass filtered resistivity data for the ARP channel and interpretation

Apparent resistivity values span over a wide range of values due to the proximity of the bedrock: from 130 to 1300 for channel1 (0 to 0.5 m); 120 to 1400 (0 to 1 m) and 100 to 2100 for channel 3(0 to 1.7 m). In order to better observe the results, we show filtered maps, i.e., with the regional component removed. For convenience, we separated the study area into two zones, labelled zone 1 and zone 2. Zone 1 shows a set of coherent and clear conductivity anomalies. The resistive anomalies

form a rather regular rectangular polygon of 42 m by 17 m. They are surrounded by conductive anomalies which seem to go around them. They are probably located between 50 and 100 cm below ground level. The impact on the third track in zone 1 is minimal. In zone 2, only resistive anomalies appear. They are interlocked and superimposed, making interpretation more difficult. The anomalies in this zone are visible on all three tracks, placing them 50 to 170 cm underground.

With XRF, it is possible to analyse a large number of chemical elements, but not all of them are relevant for archaeological interpretation. For example, silicon (Si) and aluminium (Al), the components of aluminium silicates which are widespread in the earth, are particularly prevalent in soils. It is generally not interesting to represent them. We show them in the article, alongside iron (Fe) concentrations, as the representations of these three elements show very similar distribution patterns (Fig. 4).

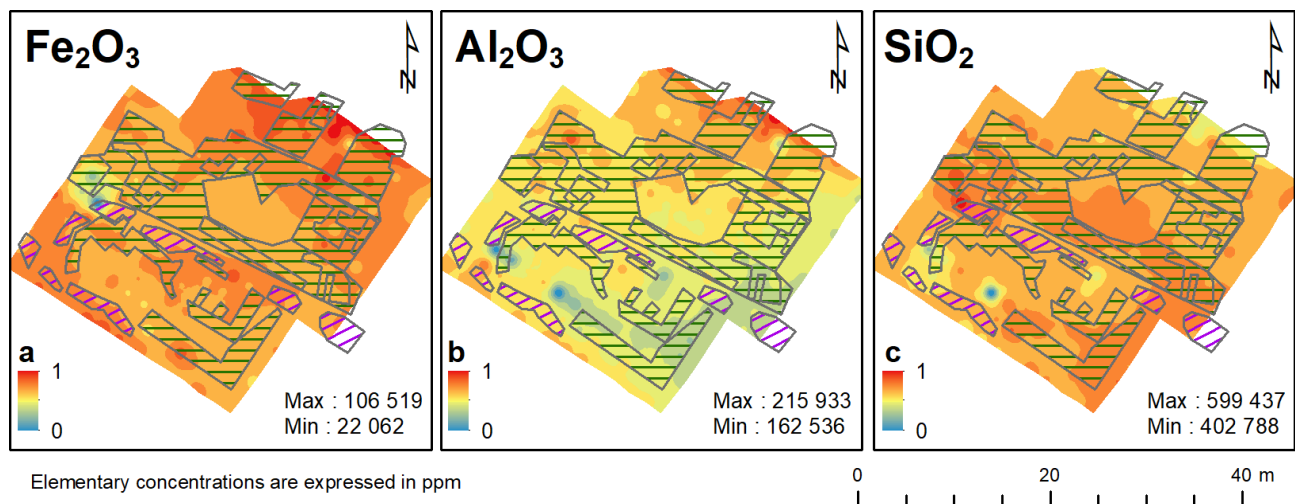


Fig. 4 – Interpolation of concentrations of iron (a), aluminium (b) and silicon (c)

Given the initial assumption of a workshop containing a small forge, we represented commonly used metals by ancient societies, namely tin (Sn), zinc (Zn) and copper (Cu), in addition to iron (Fig. 5). These metals can be used to make alloys but can also be present as impurities in ores.

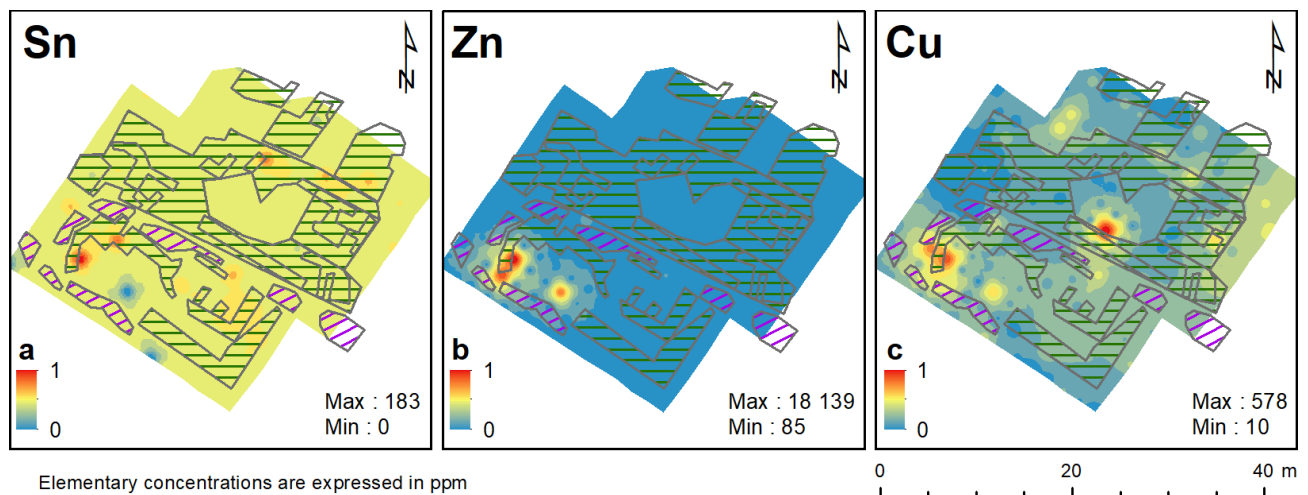


Fig. 5 – Interpolation of concentrations of tin (a), zinc (b) and copper (c)

The pH, calcium (Ca), phosphorus (P) and sulphur (S) show a highly polarised distribution (Fig. 6 and Fig. 7). All the high values of these elements are found in zone 1 defined above, i.e., the lower part of the study area.

The other elements with significant variations but which will not be interpreted further in this article are available in the supporting informations section.

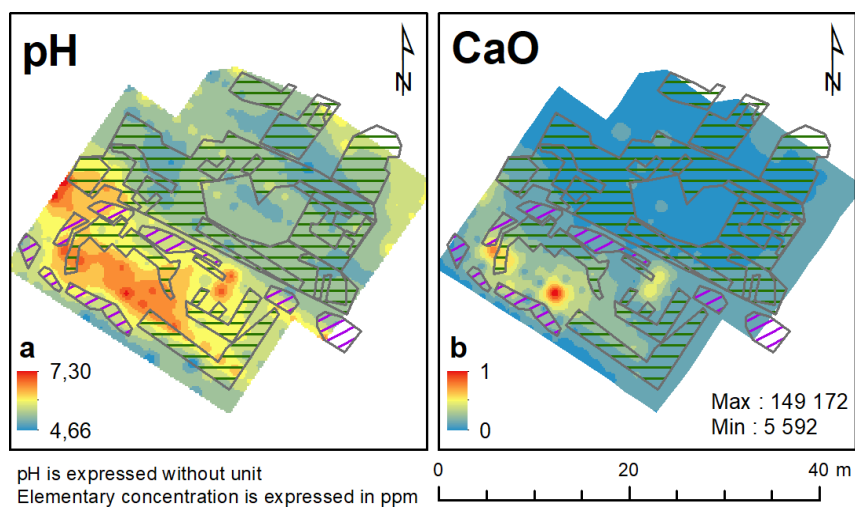


Fig. 6 – Interpolation of pH values (a) and concentrations of calcium (b)

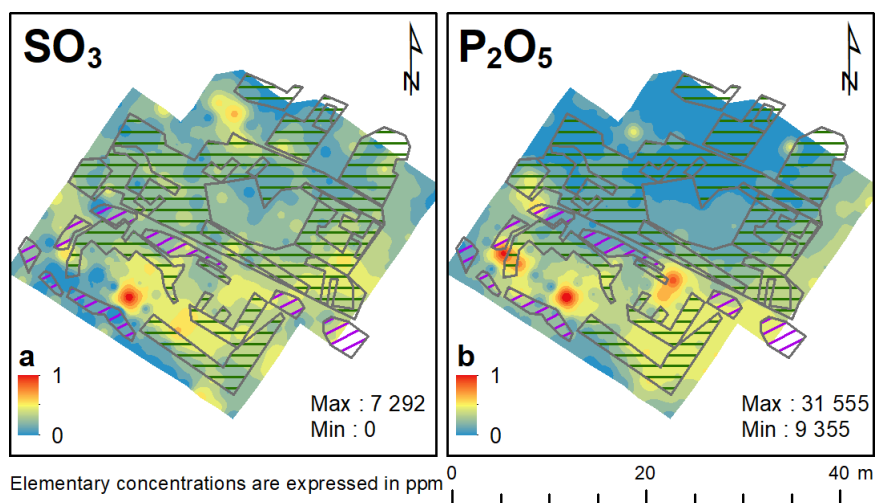


Fig. 7 – Interpolation of concentrations of sulphur (a) and phosphorous (b)

5) Interpretation

The results of the geophysical survey in the study area show numerous anomalies (Fig. 3). In zone 1, the resistive anomalies outline clear contours suggesting the presence of a building. The latter is surrounded by conductive anomalies, which may correspond to an old path or to a pipe system, either for water supply or drainage, operating with this building. Zone 2 is more complex to interpret. The intertwined signals could be the result of the superposition of several ancient occupations, but also of anomalies in the geological substratum. We should bear in mind that the monks developed their environment by creating the pond to the south of the study area, but also by cutting terraces into the rocky hillside. Local rocks were also used for the construction of the collective buildings of the abbey (Rouillard et al. 2019) and the signals in zone 2 may possibly be related to this work.

The highly polarised distribution of pH values immediately caught our attention (Fig. 6a). It seems to highlight a difference between two blocks of signals perceived by geophysical prospecting, distinguishing the northern and southern parts, respectively zone 2 and zone 1. This high pH partly overlaps with the calcium distribution zones (Fig. 6b), which is not surprising. Indeed, the presence of this element in soils increases the pH value, and it is commonly used in agriculture to reduce soil acidity. However, this is not the case here. Although the soil is particularly acidic, as the site is located in Brittany, a region of France with a granite base, it is not a question of agriculture. The presence of calcium is rather related to the presence of the structure revealed by the geophysical survey. It is specific to the architectural characteristics of the structure. Indeed, the use of limestone blocks and lime mortar leaves this type of signature in the soil. Here, given the construction materials used on the other buildings on the site, it is more likely that mortar was used than limestone blocks, which were reserved for the decorative elements of the chapter hall. The asymmetric distribution between zone 1 and zone 2 suggests that only zone 1 contains anthropic remains, whereas the anomalies in zone 2 may be more related to geological anomalies. It would be easy to confirm these hypotheses by the archaeological excavation of these zones, as initially planned. Unfortunately, the cancellation of this operation leaves these questions pending.

We can, however, answer the archaeologist's initial hypothesis of a tool maintenance workshop with a small forge. Such a structure should reveal high concentrations of the metals used in the tools. In addition, metal waste could have been detected. The observation of iron distribution (Fig. 4a) shows fairly evenly distributed concentrations. We find the same type of distribution pattern as for aluminium (Fig. 4b) and silica (Fig. 4c). It therefore seems logical to attribute the measured iron concentrations to the sedimentary matrix rather than to anthropogenic activity. Iron is also naturally present in all soils, but in cases of metallurgical activity, it is still possible to show the enrichment of the soil with iron. We were able to observe this distribution at other archaeological sites. In addition, we analysed the other metals commonly used in metalworking in former societies, namely tin, zinc and copper. Tin also shows a very homogeneous distribution, suggesting that it is also a constituent of the sedimentary matrix (Fig 5a). Zinc (Fig 5b) and copper (Fig 5c) show specific peaks, which partly coincide in zone 1. The presence of these elements is undoubtedly due to human activity, but it is difficult to affirm that this corresponds to intense ancient metallurgical activity. On the other hand, light metallurgical activity might not have left visible traces.

Indeed, it is not impossible that these metal concentrations correspond to waste fires made by the former operators of the site. According to information obtained from the testimony of the site's custodian for the Conservatoire du Littoral, these practices are contemporary. Indeed, he observed the remains of fireplaces demonstrating such practices when the site was acquired by the Conservatoire, although he was unable to pinpoint their precise location. The initially planned excavation would have helped to clarify this point but it did not take place.

However, if the hypothesis of a workshop exclusively for the forge no longer seems relevant, the distribution of the two remaining chemical elements leads us to propose another interpretation for zone 1. Phosphorus also shows a highly polarised distribution, with high values in the south of the survey area, called zone 1 (Fig. 7b). Phosphorus is an element traditionally linked to farming areas in archaeology. In reality, phosphorus seems to be a more general marker of the presence of organic matter, and not exclusively faecal. Indeed, phosphorus can be found in burials, storage areas or even food preparation areas. Nevertheless, on this site, the hypothesis of a building for housing livestock appears to be the most likely. If we observe sulphur concentrations (Fig. 7a), we notice once again that all the high concentrations are in zone 1. The enrichment of soils in this element is generally due to the presence of livestock, as a result of the accumulation of urine and external envelopes (hair, skin, nails, etc.) (Shand 2002, Kear & Watkinson 2003). Thus, while phosphorus alone cannot be used to accurately identify a livestock structure due to its ubiquitous nature in organic matter in general, the combination of phosphorus and sulphur is more relevant. Here, in zone 1, both phosphorus and sulphur are present. The abbey's rare archives indicate the presence of horses and cattle in the

inventory prior to the sale of the abbey during the Revolution (Rouillard et al. 2019). It is obviously not possible to affirm that these animals lived in this building, but this does confirm that there were livestock on the site. Finally, if we look at the interpretation of geophysical anomalies, we observe a resistant anomaly in the shape of an E in the eastern part of zone 1 which could possibly be stalls to accommodate the animals.

Although it is not possible to propose a date, it should be noted that the building does not figure in eighteenth century texts and plans, nor in the revolutionary inventory (Rouillard et al. 2019). This shows that the memory of this building had disappeared for a very long time by the time those documents were created. It is therefore possible that this building disappeared at quite an early stage, perhaps in the late medieval, early modern period. Buildings with the same characteristics - rectangular building, multiple activities - and similar dating have been observed in the abbeys of Morimond (Rouzeau et al. 2015) and Preuilly (Blary 2021). They were characterised during the excavations of these abbeys as multi-purpose buildings. Although we could not observe any traces of metallurgy at Saint-Maurice, perhaps as a result of very limited activity, we can nonetheless suggest that the probable building in zone 1 was associated with the corpus of these polyvalent buildings.

6) Conclusion and discussion

The results of this study highlight the importance of prospecting prior to more invasive archaeological operations. Geophysical prospecting revealed the buried remains of unknown structures, which do not appear in any of the ancient documents of Saint-Maurice Abbey. Geochemical prospecting clarifies the results of geophysical prospecting. It was deployed on the structures revealed by the first survey, and seems to distinguish anomalies due to archaeological remains from those due to irregularities in the geological substratum in zone 2. It is possible that the signals in this zone are evidence of the anthropization of the hill by the monks. But the chemical analysis of the sediments can go further. The initial working hypothesis of a tool maintenance workshop with a small forge is challenged by the absence of characteristic chemical soil pollution. It is possible, however, that light and very occasional activity may have left few chemical traces of this activity in the soil. On the other hand, other chemical elements found in the building in zone 1 seem to indicate the presence of livestock. The geochemical survey thus enables us to propose a new interpretative hypothesis. The probable building identified by the combination of prospecting data may be reminiscent of the multi-purpose buildings found on other Cistercian abbeys (Rouzeau et al. 2015, Blary 2021). It should be noted, however, that these latter buildings show marked traces of metallurgical activity despite their status as small workshop forges, whereas such traces seem to be absent at Saint-Maurice. Unfortunately, it will not be possible to verify this interpretation as no excavation work will be conducted at the site, contrary to initial plans.

The two prospecting techniques discussed in this study cannot be placed in competition with each other and are best used together. The advantage of geophysical prospecting is that it is easily applicable over large areas and effectively locates the geometry of buried structures, but at the same time it cannot always precisely identify what it reveals. Geochemical prospecting necessitates a large number of samples, and is thus difficult to apply to large areas with a fine grid. In addition, it records all the activities that have taken place in the area, without being able to distinguish between the different phases of occupation. Moreover, the processing and analysis of samples takes longer than for the production of soil resistivity images. However, in the same way as for geophysical prospecting, the study of chemical pollution deposited in soils helps to locate archaeological structures but also to characterise them. The combination of the two techniques provides the archaeologist with a sharp tool for approaching an archaeological site and planning future operations there. In the present case, it was possible to overcome the indeterminacy of the geophysical survey results with the help of chemical soil analysis. It was also possible to distinguish a likely archaeological structure from a probable geological signal. The prior location of remains using the soil resistivity technique enabled us to set up a narrow sampling grid, and geochemistry was used to enhance interpretations. This

technique is not intended to replace a traditional excavation operation as it does not provide sufficient information used alone, at least not in terms of dating. Nonetheless, soil prospecting and its initial interpretations can help the archaeologist to choose the best zone for operations and to anticipate the specialised techniques to be implemented. The chemical study of soils yields interesting prospecting results, especially if it is backed up by geophysics, so that it can target the probable remains. The geochemical analysis procedure is relatively long, but the time required could be reduced if all or part of the analyses were conducted directly in situ. In any case, it seems more interesting to carry out sampling and chemical analysis directly on archaeological levels, as the signal is stronger there, and the different areas can be characterised more precisely, partly compensating for the bias of superimposed activities. It should be noted that this does not in any way conflict with traditional stratigraphic excavations. As samples are taken once the study of the level has been completed, the geochemical study focuses on sediments that would otherwise have been discarded on spoil heaps. However, information obtained by the chemical analysis of the soils must still be cross-referenced with the archaeological results in order to propose the most relevant interpretations.

Supporting information

In this section, we present the elemental concentration maps not interpreted in this article. We also make available data acquired by XRF.

Conflict of interest

We have no conflict of interest to declare.

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