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Scientific advances in geoarchaeology during the last twenty years

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A B S T R A C T

Advances in areas of archaeological science with a strong geological, sedimentological or pedological component have significantly furthered the understanding of formation processes, improved interpretations and helped develop site preservation over the last twenty years. Here, we examine some of those subject areas and their progress, with a view to charting future directions for this growing body of knowledge.

1. Introduction

The last twenty years have seen an enormous growth in the use of earth sciences in archaeology. This type of work has become known *de facto* as geoarchaeology, but there has never been a sense of clear boundaries to the subject area, and a broad spectrum of techniques and approaches are often included. We have selected studies from that spectrum in order to point out the innovations and major growth areas – i.e. to showcase the quality of science rather than to follow a defined a subject area. The lack of boundaries, however, means that those choices often approach other subject domains; so some quite sharp cut-offs inevitably appear in relation to other articles in this special issue of *JAS*. To try and organise the diverse selection of research highlights, we have worked under three main headings – Site Formation Processes, Interpretative Studies, and Taphonomy and Preservation.

2. Site formation processes

2.1. Cave sediment diagenesis

Probably the most comprehensive advance in our understanding of site formation processes over the last two decades has come about in the study of cave sediments. Caves containing mainly clastic sediments have benefitted from considerably improved understanding, and this is expanded on elsewhere (see Hunt et al., 2015). However, a very different type of cave fill has also been the focus of intense study in the past twenty years, particularly involving micromorphology and FTIR spectroscopy. Owing mainly to reduced throughflow of water, some Mediterranean and tropical caves contain a remarkable suite of sediments primarily modified from biological remains and often deeply stratified. These deposits are mainly introduced by humans, livestock and bats, but also include inputs from rockfall and occasional wild animals.

The major constituents are ash, dung, guano and bones. Ash is formed either from open fires, burnt livestock bedding material or burnt dung. It is made up chiefly of calcium carbonate where trees and shrubs have been the source material, and opaline silica where the fuel was derived from grasses. The calcium carbonate component consists of calcite pseudomorphs of the calcium oxalate crystals that are abundant in the trees and herbs (Fig. 1). The origin of this material was first demonstrated by Folk (1973) and later elucidated by Brochier (1983, 1996; Brochier et al., 1992; Brochier and Thinon, 2003). These papers showed details of the thermally-induced calcium oxalate breakdown, followed by calcium carbonate replacement, either directly (at low-temperatures) or by recarbonation from atmospheric CO_2 after higher temperature burning. The siliceous component of ash is mostly morphologically unchanged phytoliths or silica skeletons, except where alkaline salts flux the silica and produce ash melts (Folk and Hoops, 1982; Thy et al., 1995; Canti, 2003; for further details of this material see Dynamics and products of fire, below). Original dung can be found unburnt in some situations (Shahack-Gross, 2011; Brochier, 2002), but it is more typically ashed, in which case the stratigraphy will often end up dominated by faecal spherulites. These are tiny (5–20 μm) radially crystallised bodies of calcium carbonate

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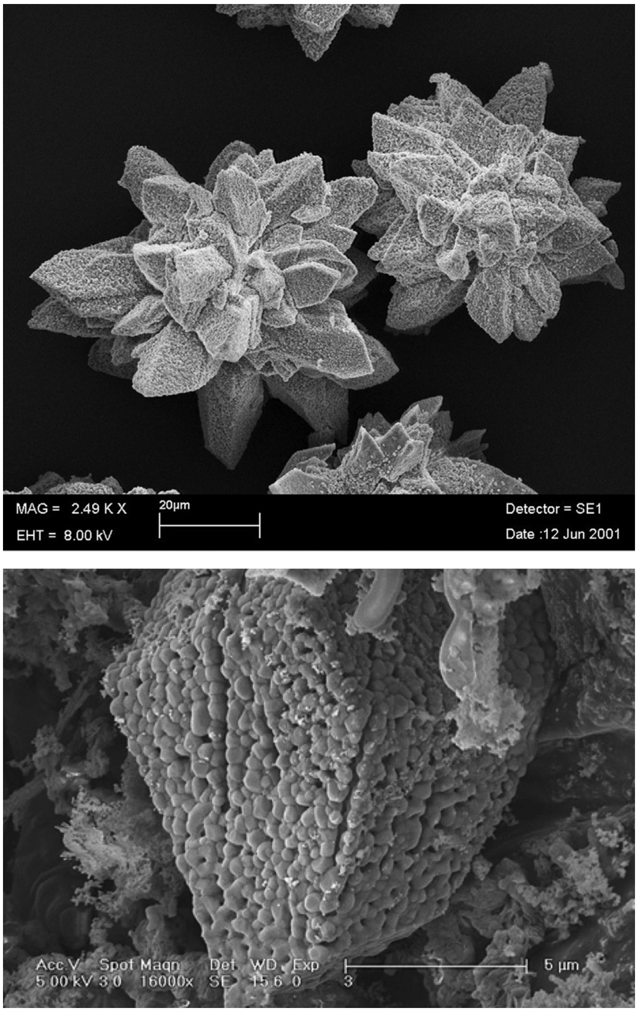

Fig. 1. Druse (upper) and prismatic (lower) forms of calcium carbonate pseudomorphs after calcium oxalate. Both these oxalate crystal forms are very common in trees and shrubs throughout the world, and the pseudomorphs form a major component of ash. Photos — upper from Canti (2003) and lower from Shahack-Gross and Ayalon (2013).

formed in the gut of many animals, but especially herbivores. They were discovered and identified by Brochier (1983, 1996) and Brochier et al. (1992), then subsequently studied in detail by Canti (1997, 1998, 1999) and Shahack-Gross et al. (2003). Further details of spherulites appear under Dynamics and products of fire, below.

From a chemical standpoint, both the faecal spherulites and pseudomorphs of oxalate are simply fine-grained calcium carbonate. Since many of the caves are also made of limestone, there is a preponderance of calcium carbonate ready for reaction with other chemical inputs to the system.

These reactions were first examined at et-Tabun cave by Goldberg and Nathan (1975) who noted the formation of dahllite (carbonated Ca phosphate) where solutions containing bone dissolved by uric and humic acids or bat guano come into contact with calcite. Crandallite (Ca, Al phosphate) and montgomeryite (Ca, Mg, Al phosphate) were formed where the calcite was restricted. A similar understanding of bone dissolution was used by Weiner et al. (1993) to develop a model for which parts of the Kebara Cave were likely to have lost their original bone content and which were not. This was based on mapping the mineral phases present in the sediments using portable FTIR, and comparing the results with the bone condition and distribution.

Further examination led to a more detailed understanding the mineral types, including those occurring in similar suites in Theopetra cave (Karkanas et al., 1999) and siliceous residues in Hayonim (Schiegl et al., 1996). A landmark theoretical analysis of the authigenic minerals in caves was produced by Karkanas et al. (2000), showing the reaction cascades produced on the rims of carbonate rock fragments, and the potential they have for determining past conditions. Stiner et al. (2001) showed a good correlation in Hayonim cave between bone weight recovered and intact calcite and dahllite. Areas of poorly preserved wood ash and lower bone content correlated with higher siliceous components, montgomeryite and leucophosphite (K, Fe phosphate). However, the areas of low bone content also contained some individual well preserved bone, explained as the result of bioturbation.

A significant step forward came when Karkanas et al. (2002) demonstrated that the presence of newberyite (hydrated $MgHPO_4$) could be directly related to past guano deposits in Grotte XVI, Dordogne. Newberyite is an in situ transformation product of struvite, (hydrated NH_4MgPO_4), which is a primary component of fresh bat guano. Once deposition ceases and ammonia levels produced by the fresh guano drop, the transformation of struvite to newberyite is automatic.

Shahack-Gross et al. (2004) took the examination of bat guano diagenesis to a greater level of detail in six different Israeli caves. They found that insectivorous bat guano is both more acidic and also richer in phosphate than fruit bat guano. Particular diagenetic pathways tend to occur in micro-environments often localised within caves rather than being universal. The locations of these micro-environments are decided by precise factors such as the presence of bat roosts above the sediment, or the exact path of water through it. This means that intimate knowledge of the diagenetic pathways has to be applied individually to determine the completeness of the archaeological record in any given cave. Echoing this point in a discussion of Hayonim cave, Weiner et al. (2002) said "*Although each cave is unique, sufficient knowledge from different caves in diverse environments is now available that shows that many of the underlying processes observed in Hayonim Cave are common to other cave environments*."

Since the blossoming of FTIR-based cave diagenesis studies in the late 1990s and early 2000s, further minerals have been discovered, particularly the more soluble (and thus rarer) species e.g. gypsum and nitratite ($NaNO_3$) in Cova des Pas on Minorca (Cabanes and Albert, 2011) and Diepkloof Rock shelter, South Africa (Miller et al., 2013). This latter site also contained sveite (a hydrated K, Al nitrate) and nitre (KNO_3) as identified by XRD. Research has continued into other important chemical and morphological aspects of cave fills. Efforts to provide a clearer distinction between ash $CaCO_3$ and cave wall limestone first involved the comparison of different calcite peaks produced by infrared analysis where recrystallisation had not occurred (Regev et al., 2010), and later the use of C and O isotopes because of the differences in the original isotopic composition of the plant matter, air and limestone which form the inputs. The study led to the discovery that the ash itself has different isotopic compositions (Shahack-Gross et al., 2008a), arising from the different fractionations associated with high or low temperature transformation of calcium oxalate into calcium carbonate. The isotopic composition of archaeological ash can thus be shown to reflect mixing lines involving the original plant matter, as well as atmospheric and geological inputs (Shahack-Gross and Ayalon, 2013).

The refined understanding of site formation represented by these studies has led to further developments in methodology and interpretation. The mineralogical distinctions were put to use by Mercier et al. (2007) to refine the TL dating of heated flints from the Mousterian layers of Hayonim. A detailed examination was performed showing that dose-rate values could be systematically related to the sediment mineralogical type. The information was combined in order to assess the dose-rate experienced by each flint during its burial. Some of the $CaCO_3$ distinction methods were able to show ash recrystallisation at Qesem Cave, Israel (Karkanas et al., 2007) and more recently at the same site, refined FTIR of clays (Berna et al., 2007), together with both standard sediment micromorphology and FTIR microspectroscopy were combined to show repeated use of a Lower Palaeolithic hearth (Shahack-Gross et al., 2014). A combination of micromorphology and FTIR microspectroscopy was used to provide unambiguous evidence that burning took place in Wonderwerk Cave, South Africa, during the early Acheulean occupation (Berna et al., 2012).

2.2. Dynamics and products of fire

The use of fire is seen as one of the main steps in the development of modern humanity and has been a constant in many activities, including food procurement and preparation, heating, artefact production or modification, land management and ritual practices. Consequently, burning is amongst the most common site formation processes, but many aspects are still unclear. The last two decades have seen a major increase in our understanding of fire use, and an important broadening of the techniques employed to research it.

2.2.1. Charcoal

Charcoal has a high potential of survival, and is therefore a widespread indicator for fire and fuel. It is commonly formed by incomplete combustion in oxygen-starved areas of a fire. Braadbaart and Poole (2008) distinguished between carbonization (heating in the absence of air) and charring (heating in restricted air). They demonstrated that the largest loss of mass occurs between c. 200 and 350 °C, but that chemical alterations continue until c. 800 °C. Until recently, it was generally assumed that charcoal consists of graphite-like carbon. For example, based on a combination of techniques including TEM, FTIR, XRD, TGA/DTA, ESR and Raman spectroscopy, Cohen-Ofri et al. (2006) proposed that fresh charcoal consists of graphite-like microcrystallites mixed with a non-organized phase, with fossil charcoal appearing to be altered – especially by methylation. DTMS-EI and elemental analyses by Braadbaart and Poole (2008), however, indicated that charcoalification entails the formation of aromatic compounds, culminating around 800 °C in a benzene-dominated composition. Similar results were reported by Styring et al. (2013) for charred wheat grains. Ascough et al. (2011) and Cohen-Ofri et al. (2006) found C=C bonds and aromatic CH deformation in charcoal FTIR spectra, confirming the presence of aromatic compounds, but retain the graphite-dominated model. Further research is needed to resolve this issue.

Whether the charcoal is dominated by graphite-like or benzene compounds, recent publications make clear that the material is less inert that often thought. Cohen-Ofri et al. (2006) argued that a process of carboxylation or "self-humification" causes changes between fresh and fossil charcoal. Ascough et al. (2011) demonstrated that alkaline extraction of charcoal can result in dissolution of significant amounts of the charcoal mass. Laboratory experiments by Braadbaart et al. (2009) indicated that the sensitivity of aromatic compounds to alkalis may result in damage to charcoal by alkaline burial conditions. Huisman et al. (2012) interpreted a combination of micromorphological evidence for charcoal disintegration and the presence of thick limpid clay coatings visible in thin sections from early Neolithic pits in the Netherlands as evidence for charcoal disintegration due to ash-induced alkalinity.

Microscopic study of archaeological charcoal sometimes reveals changes in the structure of preserved wood cell walls, starting with local fusion of anatomical constituents in its early stages, progressing to total fusion and homogenisation into a dense, often vesicular mass (Marguerie and Hunot, 2007). This process is frequently referred to as vitrification - a confusing term as vitrification is the change from a substance into a glass. McParland et al. (2010) were not able to reproduce vitrification in the lab, either at high temperatures or by using green wood. Based on chemical properties, Braadbaart and Poole (2008) linked this material to tar. More experimental work is needed to elucidate its origin and implications.

2.2.2. Phytolith deposits

Although it has been known for a long time that burnt monocotyledon plants produce ash dominated by silica phytoliths (e.g. Baker, 1968; Zeuner, 1959), it is only during the last decade that geoarchaeologists using micromorphology have become aware that thick, extensive phytolith deposits with a groundmass dominated by silica occur in many regions, site types and archaeological periods. They usually do not form recognizable hearths or burnt features, but most commonly occur as laterally extensive bands or thicker deposits characterised by a groundmass consisting of finely laminated, articulated silica phytoliths with associated fine carbonized plant material. Miller and Sievers (2012) described such deposits found in Palaeolithic deposits in the Sibudu cave (South-Africa) and interpreted them as resulting from construction, maintenance and burning of bedding. They also carried out experimental work on the results of burning dried monocotyledon plants (grass, reeds, sedge or straw); a stack of dried plants would yield a phytolith deposit c. 5% of its original thickness (see also Miller et al., 2009). Shillito and Matthews (2013) described similar deposits in the Neolithic proto-urban Çatalhoyük where they interpreted them as middens. Huisman and Raemaekers (2014) found a similar c. ½ m thick Middle Neolithic deposit in Swifterbant (The Netherlands) and they also interpreted it as a midden. Huisman et al. (2014) indicated, on the basis of the density in microCT-scans of a sample from the Swifterbant S4 midden, that the carbonized remains associated with the phytoliths are in fact also phytoliths, but ones that contain charred organic material.

In the Belesta cave (France), Brochier and Claustre (1999) found Neolithic to Bronze Age deposits which they interpreted as burnt stabling material. These had a groundmass dominated by finely laminated articulated phytoliths and microcharcoal, but also including some horizons that contained (wood-derived) calcium carbonate ashes. Most of the thin bands with phytolith-dominated groundmass in Iron age deposits in Tel Dor (Israel) described by Shahack-Gross et al. (2005) and Albert et al. (2008) were also thought to be burnt stabling deposits based on the presence of faecal spherulites (see below).

Not all phytolith-dominated deposits are the result of fire. In the same Tel Dor site, one layer of pure phytoliths lacking carbonized material, and intercalated between ash deposits is thought to have been formed by the decay of herbivore dung (Shahack-Gross et al., 2005; Albert et al., 2008). Non-charred organic tissue laminae between pure silica phytolith deposits in the base layers of the Swifterbant S4 midden (Huisman and Raemaekers, 2014) are probably the last organic remnants of the decayed plants that formed these deposits. Mousterian deposits in Esquilleu Cave (Cantabria, Spain) were found to contain bands of articulated phytoliths, interspersed with deposits of wood ash and burnt bone (Mallol et al., 2010). Based on the refractive index of the phytoliths, which showed no evidence for heating, Cabanes et al. (2010) argue that these deposits represent alternations between hearth rake-out and decayed bedding (see below).

Most of the accumulations discussed above rely on the low solubility of phytoliths in many archaeological situations. Little experimentation on this important topic has been carried out in the last twenty years, but one study showed that the stability of modern wheat phytoliths in laboratory dissolution experiments varies with the part of the plant that they come from, and whether they are burnt or not. Furthermore, some morphotypes can come to resemble others due to dissolution and abrasion (Cabanes et al., 2011). Conversely, the loss of the matrix around the poorly-soluble silica entails very large reductions in the volume either by dissolution (Schiegl et al., 1996) or decay processes (Shahack-Gross et al., 2005), and this produces notable effects on both the macro- and microstratigraphy (Albert et al., 2008).

Faecal spherulites (see also Cave sediment diagenesis, above) in sediment samples or thin sections are used increasingly as a positive indicator for the presence of (burnt or unburnt) herbivore dung. Canti (1999) demonstrated, however, that formation of these spherulites depends on the diet of the herbivore, only being formed if the fodder comes from alkaline soils. He also showed experimentally that spherulites dissolve easily in non-alkaline conditions – later confirmed by Lancelotti and Madella (2012) and Gur-Arieh et al. (2014). Absence of spherulites does not, therefore, preclude a (burnt) herbivore dung origin for phytolith-dominated deposits.

The types of contributing fuel are important as well. Braadbaart et al. (2012) found that peat ash showed mixed properties, combining high calcium contents and alkalinity with the presence of silica phytoliths. Cow dung ash was dominated by silica phytoliths, with high contents of phosphates being a distinguishing feature. Albert et al. (2000, 2012) indicated that the presence of monocotyledon silica phytoliths in mixed ashes in Mousterian deposits in Kebara Cave (Israel) may derive from contamination of grasses and similar plants adhering to wood, and does not necessarily mean that mixed fuels were used.

There are many examples where opal phytoliths show evidence for (partial) melting, resulting in deformations or in the occurrence of glassy slag fragments embedded in ash deposits (see e.g. Mentzer, 2012). In extreme cases, large glassy slag chunks may form. Thy et al. (1995), who investigated such glassy slags in Botswana, assumed that temperatures of 1155–1290 °C were needed to melt the silica. After comparing the chemical composition of dung and glassy slag in Iron Age South African burnt kraals, Huffman et al. (2013), argued that the K_2O contents are too low in the glassy slag to be derived from dung. They proposed that additional potassium must have been derived from wood, i.e. the wooden fence that surrounded the kraal. Photos-Jones et al. (2007) described how large glassy slag lumps were made on purpose in prehistoric Orkney cremation burials by burning a mixture of herbivore dung and seaweed; the high concentrations of alkalis in both dung and seaweed may have lowered the melting temperature of the silica.

2.2.3. *Effects of fire on stratigraphy and archaeological materials*

In the absence of ash or charred remains, reddish (rubefied) soil is often seen as a clear indication of fire. Its reddish colour can in some cases result in rubefied soil being misinterpreted as ochre (Crombé et al., 2014). Experiments by Canti and Linford (2000) demonstrated that the soil underneath open fires rarely reaches temperatures above 500 °C, which would be needed for the iron oxide mineral transformations that cause the rubefication. Moreover, they found that the relationship between reddening and temperature is not straightforward, with some soil showing unexplained rubefication at lower temperatures than expected while other soils do not show any effects at much higher temperatures. Using clay and calcium compounds' changes in FTIR-spectra, Gur-Arieh et al. (2013) measured the maximum temperature that different parts of traditional cooking installations may have been subject to. Despite temperatures reaching 700–900 °C in these installations, they found that outside samples usually show no evidence for heating and samples from the inside gave variable results.

Berna et al. (2007) found progressive changes in FTIR-spectra of clay minerals and clayey soils with increasing temperatures between 500 and 1100 °C. They used these changes as a palaeothermometer to determine the degree of heating of specific strata in the Late Bronze Age and Iron Age deposits of Tel Dor (Israel). Still, experiments by Mallol et al. (2013a) showed that many of the human activities related to fire – including relighting and cooking – leave no trace in the archaeological record detectable through studying ash or charcoal deposits with conventional techniques. Activities that can be detected – like trampling and sweeping – are essentially post depositional.

Sievers and Wadley (2008) showed that carbonization of fruits in Middle Stone Age deposits in South African rock shelters is likely to have occurred while they were buried 5–10 cm below the actual fire. In a comparison of experimental work with Middle Palaeolithic hearth features from El Salt (Spain), Mallol et al. (2013b) investigated black soil horizons that are often found as part of flat hearth features. They demonstrated that such layers may not consist of fuel remains, but rather are formed by heating soil. Both studies show that carbonized remains may be related to human activities predating and unrelated to the fire.

Several methods to estimate the heat produced in a fire have been developed and applied (see also the extensive review by Mentzer (2012)). Braadbaart and Poole (2008) and Ascough et al. (2010) demonstrate that mean random reflectance measurements on charcoal showed a good correlation with the production temperature between 200 and 1200 °C, and therefore can be used as a paleothermometer. However, Braadbaart et al. (2009) demonstrated that exposure to alkaline environments – as may occur when charcoal is buried in ash-containing soil environments – may result in significant decrease in reflectance, and could therefore lead to an underestimation of the temperature. Elbaum et al. (2003) showed that the refractive index (RI) of silica phytoliths changes on heating. They demonstrated that if the majority of extracted phytoliths have a RI > 1.440, the material has probably been heated to temperatures >500 °C.

Several researchers have investigated the effects of heating on calcareous materials. Villagran et al. (2011) experimented with heating shells to temperatures from 200 to 800 °C, and produced a series of morphological changes that can be observed in thin sections. This includes inner layer fissuring at 300 °C, re-orientation of calcite crystals and increased birefringence at 400 °C, shattering at 500 °C, formation of fibrous calcite on the outer layer at 600 °C and complete shattering and decrease of birefringence at 800 °C. Toffolo and Boaretto (2014) showed that aragonite can form if calcareous material is heated above 600 °C. This pyrogenic aragonite can be detected using FTIR.

Bone is often found in fires. Mentzer (2012) showed how FTIR analyses on bone can be used for determining maximum heating temperatures because of progressive changes in the bone mineral due to heat exposure. This application that has found uses especially in Palaeolithic settings (e.g. Goldberg et al., 2012).

There are now an increasing number of studies giving indications of temperature-based changes to stratigraphy, artefacts and biological materials. Few, however, clarify the duration of heating and redox conditions under which such changes occur. For the future, these extremely important variables need to be included in experimental results if the true interpretative value is going to be obtained.

3. Interpretative studies

3.1. Phosphate and multi-element soil analyses

The measurement and mapping of soil chemical characteristics on archaeological sites has burgeoned beyond anything that could have been imagined in 1994. The earliest approaches were mostly phosphate-based and papers describing this type of testing have been regularly produced throughout the intervening years. In some cases, these contained innovations, usually methodological, such as refinements to the extraction procedure (Terry et al., 2000) and the Eidt (blue ring) test (Bjelajac et al., 1996), details of the complexities of the different P fractions (Schlezinger and Howes, 2000) and rapid field testing for mapping (Rypkema et al., 2007). However, the technique has not been able to provide either the survey or interpretative detail that it seemed to promise with the original discovery of P fixation in anthropically-modified soils in Sweden, and the pioneering publication by Arrhenius (1931) (see summaries of the history in Linderholm and Lundberg, 1994; Middleton and Price, 1996; Wells et al., 2000). With the advent of widely available ICP spectrometry for cheap elemental analysis, it was inevitable that the focus would expand from phosphate alone to multi-element analysis (which usually includes total P), since the additional elements ought to give additional information.

Early results showed that activity areas in a modern house compound could readily be distinguished on the basis of chemical residues in soils and that features such as floors, and hearths could be distinguished from each other and from the natural prehistoric ground surface (Middleton and Price, 1996). There were methodological innovations, for example Entwistle et al. (1998) who found that although ICP-MS was capable of rapid cheap testing, it showed some detailed problems of scaling and spectral interference which meant that supplementary testing was also needed in some situations.

Wells et al. (2000) showed a remarkable correlation between archaeological features and certain elements at the Mayan settlement of Piedras Negras, Guatemala. High phosphate concentrations were found to be good indicators of kitchen middens; other types of waste, characterised by relatively high levels of heavy metals could have come from workshop, craft, or ceremonial activities. In addition, a pattern of heavy metal concentrations suggested that walls had been painted with some brightly coloured oxides, hydroxides, carbonates and sulphides, particularly of Fe, Cu and Hg (Fig. 2).

Stimulated by the new possibilities, numerous studies then appeared using the technique in a mapping mode and then correlating results with existing archaeological interpretations. At Calleva Atrebatum (Silchester, UK), for example, Cook et al. (2005) found concentrations of Pb, Zn, Cu, Au, Ag and Sn. These were explained as resulting from various manufacturing processes, but origins resulting from bioturbation were also invoked where the concentrations were not associated with hearths. Cook et al. (2006) found concentrations of Au, Hg and rare earth elements at Cancuén, Guatemala. Although these could mostly be interpreted as the result of occupation and industrial activity, the case of Au was particularly difficult as gold was thought to have been absent from the Classic period Maya world. The problem presented by these studies, and numerous others in the genre is that, however good the work, the interpretation of elemental concentrations is usually going to be equivocal. In an effort to improve this situation, various fresh approaches have been taken in recent years. Oonk et al. (2009a) set out to improve the methodology at three Bronze Age and Roman habitation sites in different parts of The Netherlands. As well as assessing the element concentrations associated with the house plans, this study combined offsite sampling, regional background comparisons and the use of bivariate plots (Al vs. selected elements) to identify.anthropogenic elements. In a different paper from the same sites, they examined the mineralogical transformation that led to a particular enhancement and showed the complexity of the chemical relationships which could be behind each elemental reading (Oonk et al., 2009b). Milek and Roberts (2013) enhanced their element survey of a Viking house in Reykjavik Iceland with parallel measurements of magnetic susceptibility, loss-on-ignition and electrical conductivity. They also integrated the elemental results with micromorphological investigations to help provide a more complete picture of the micro-preservation environment.

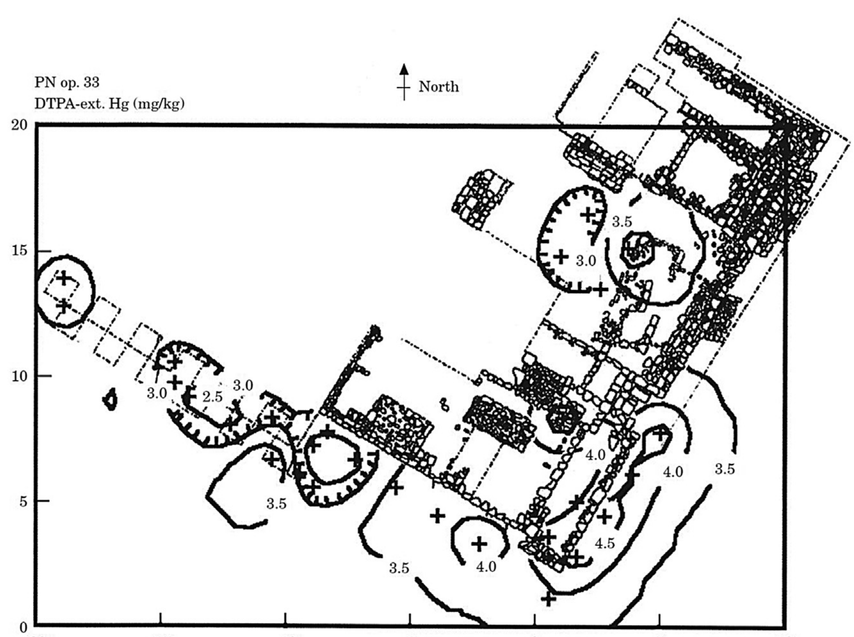

Fig. 2. Wells et al. (2000) illustration of the distribution of Hg superimposed on the Piedras Negras wall pattern.

Other papers have attempted to examine the problem by researching elemental concentrations in modern situations with measurable human activity. Wilson et al. (2005) looked at enhancement on a number of farms across the UK, and concluded that six elements (Ba, Ca, P, Sr, Pb and Zn) were enhanced at all the locations; these could therefore reliably be used as indicators of farming. The idea was developed in Wilson et al. (2009) to produce actual prediction rates for function based on elemental measurements. Although these rates were relatively good in some cases, the uncertainty remains a problem if the elemental concentrations are going to be interrogated on their own. Where atypical or unusual modern functions are tested against their elemental signatures, the results clearly show that completely unassisted interpretation would be impractical. Knudson et al. (2004), for example, found a range of enhanced elements, including Sr, underneath covered fish drying racks in western Alaska. We would have to know that fish drying racks were a likely archaeological feature before interpreting their presence only from a suite of elements in the soil. Venturing even further into the unknown, measurements by Terry et al. (2004) from the dirt floor of a late 20th century guardhouse at the Mayan site of Aguateca, Guatemala showed that, while high P represented cooking and waste disposal, heavy metal concentrations arose from the filing of machetes and the disposal of batteries. The chances of some imagined future archaeologist making the correct interpretation of these activities would seem remote.

It is surely significant that 25 years ago, a critique by Bethell and Mate (1989) described phosphate analysis as rarely in “active” mode. It was nearly always only enhancing existing archaeological interpretation. The fundamental difficulty of deciphering elemental signals remains the central stumbling block, whether it is P alone or multi-element data. This group of methods will always have a certain traction on archaeological sites, particularly where traditional interpretations are equivocal and adding as much additional evidence as possible seems the best approach. The results will only be really significant if some way of improving the interpretation could be devised.

For the future, changes may be coming at the other end of the cost/benefit equation, as we now have the advent of portable or handheld XRF (pXRF or HH XRF; see Frahm and Doonan, 2013). This is a technique surrounded by controversy (Shackley, 2010), probably because the potential for misuse is abundantly clear to archaeological scientists. Recent papers by Speakman and Shackley (2013) and Frahm (2013a,b) argue mainly around a difference in approach between those for whom analyses must be performed to the highest possible standard of accuracy and precision, and those who are prepared to trade some of that quality for a greater throughput and flexibility, provided that the readings are good enough to answer the research questions (see also The Longer Term Outlook, below).

For applications in multi-element soil analysis, special care has to be taken when measuring in the field, as moisture content, soil roughness and soil heterogeneity may seriously affect pXRF measurements. However, results have already shown that these less favourable types of situation appear, in some cases, to be capable of successful analysis. Gauss et al. (2013), for example, found that soil chemical surveying by pXRF produced repeatable results which compared well with high resolution laboratory measurements, including atomic absorption spectrometry and inductively coupled plasma optical emission spectrometry. Although readings have larger errors with direct soil measurement, they may still be useful depending on the reliability needed for the archaeological aim. Hayes (2013) tested pXRF on shallow anthrosols, and showed that it could have potential for in situ site prospection or within-site activity area prospection. Features and deposits buried deeper than 5 cm were more difficult to detect from in situ surface readings, but auger samples could be extracted for ex situ (but still rapid) testing.

There will doubtless be further methodological problems to be resolved, and a fundamental accuracy barrier may need to be accepted as the norm. However, the longer term prognosis could well be cheap elemental mapping possible at any site in the same way as geophysics. This would then obviate the cost problems of element survey in mapping mode, and lead to the addition of a new potentially valuable layer on the pre-excavation remote sensing.

3.2. Land-use, vegetation and climatic studies

Geoarchaeological approaches to land-use, vegetation and related climatic interpretation have developed two main research approaches in the last twenty years. They are not mutually exclusive, but represent significantly different methodological groupings, appropriate in different parts of the globe. The first has been the examination of physical evidence together with historical land-use analogues, where such information is still available. Cultivation of soil seems frequently to leave little diagnostic trace at the microscopic scale (Davidson and Carter, 1998; Huisman et al., 2009), but there is considerable scope for studying the materials added as manures as well as some associated practices which leave a clearer physical record. The second approach is the use of stable isotopes. The growth in general archaeological use of isotopes has focussed typically on food processing and human or animal diet (see Fiorentino et al., 2014; Makarewicz and Sealy (2015) for an overview). From a geoarchaeological perspective, the main use has been the measurement of carbon (^{13}C and ^{12}C, expressed as $\delta^{13}C$) and nitrogen (^{15}N and ^{14}N, expressed as $\delta^{15}N$) in soil organic matter (SOM) from archaeological sites and/or palaeosols in order to derive past vegetation and land-use properties.

The first research approach has been carried out mainly in the Northern Atlantic region. Here, a range of sites, often cultivated by traditional techniques until relatively recent times, have provided a strong source of data for examining the potential. Deep topsoils on Orkney U.K. form a specific soil type associated with known historic manuring practices, and particular types of Norse place name. They were studied by Simpson (1997), using a variety of techniques including phosphate, $\delta^{13}C$, particle size and micromorphology. This work enabled the identification of sources for the additions (turf, manure and seaweed) that had gradually deepened these soils, as well as textural changes associated with cultivation. Davidson and Carter (1998) were able to show numerous details of the type of manuring and local sources of materials used, but were unable to show diagnostic micromorphological changes resulting from cultivation. This approach was further amplified by Adderley et al. (2006) who were able to correlate the manuring practices with numerical evidence from image-analysed soil thin sections.

Other dark soils on Orkney, found in areas of calcareous wind-blown sand, were identified though micromorphology, isotopic and lipid analysis to be the result of manuring with turf and domestic midden waste (Simpson et al., 1998a); and a suite of similar techniques with additional pollen analysis (Simpson et al., 1998b) showed that marginal sandy and sloping soils in Norway were maintained in a suitable condition for barley production by additions of midden material, ash and turf, from around 700 AD onwards.

Adderley and Simpson (2006) broadened the scope of this type of research in order to answer larger questions. They integrated models of soil hydraulic properties with ice-core and other climatic data to show that there would have been a frequent irrigation requirement to maintain pasture productivity on Norse Greenland throughout the period of settlement until the 14th century, after which the settlements were abandoned.

For the second approach, several studies use the common property of C4 plants that they have systematically higher (i.e. less negative) $\delta^{13}C$ than C3 plants (Cerling, 1984). Since the success of C4 plants over C3 plants is climate-dependent (with C4 plants favouring warmer, drier climates), stable carbon isotope analysis has become a common technique among researchers studying past terrestrial plant communities and climates (Johnson et al., 2007a). For example, Holliday et al. (2006) found unidirectional warming from the latest Pleistocene through the middle Holocene in soil profiles linked to Paleoindian sites in the Albuquerque Basin in the central Rio Grande Valley. The most negative $\delta^{13}C$ (indicative of more cool climate grasses) in the earliest part of the record (~14,000 ^{14}C yr BP), ranging from −20‰ to −16‰ which became progressively more positive, reaching maximum values of −14‰ at ~4000 ^{14}C yr BP. They interpreted this change as resulting from an increase in C4 (warmer climate) contributions to soil organic matter of about 50%–90% over period studied.

Changes of $\delta^{13}C$ in SOM with depth should be interpreted with caution, however. Johnson et al. (2007a), in a study of modern analogue steppe soils in Kansas, interpreted down-profile increases in $\delta^{13}C$ as resulting from a larger contribution of shallower − rooting C3 plants to the soil organic matter (SOM) pool in the upper horizons, whereas C4 plant roots provide the bulk of the SOM at deeper levels.

Several studies have employed the fact that maize (*Zea mays*) is a C4 plant, and that its introduction as crop therefore could have had a major impact on the SOM $\delta^{13}C$. Webb et al. (2004) used the different organic matter fractions to study how the SOM $\delta^{13}C$ profiles changed through time after abandonment of a maize plot in a C3-dominated ecosystem in Belize. Four stages of SOM breakdown and fresh organic matter addition to the soil profile were demonstrated, during the introduction of maize (causing high $\delta^{13}C$ in topsoil, and low values in subsoil) and up to 1000 years after abandonment (changing to low $\delta^{13}C$ in topsoil, and high values in subsoil). In the Mayan Lowlands of Guatemala, the SOM $\delta^{13}C$ at varying depths in 23 locations showed that 65% of the soil profiles had been repeatedly cleared for agricultural use by C4 plants, probably maize (Johnson et al., 2007b). Webb et al. (2007) added a spatial dimension by showing, through isotope signals, that maize production was slightly favoured on the flatter regions of crests or bases of hills in the soils around the Maya centre of Motul de San José (Guatemala). Similarly, Johnson et al. (2007c) found that seasonal wetland soils in the Petexbatún Region of Guatemala have high $\delta^{13}C$, whereas permanent wetlands have low $\delta^{13}C$. They derived from this relationship that the Maya of Aguateca grew maize on the rich soils of the toe slopes.

Shahack-Gross et al. (2008b), investigating modern and archaeological livestock enclosures in Kenya, found generally higher $\delta^{13}C$ in cattle enclosure sediments than in soils rich in dung from caprines (sheep and/or goat). This was thought to be caused by different feeding behaviours between the animals in this region, with cattle grazing on C4 vegetation and caprines browsing on a combination of C3 and C4 plants. They also found elevated $\delta^{15}N$ in soils of livestock enclosures and thus demonstrated that herbivore dung has elevated $\delta^{15}N$ values over that of the ingested plants. Using elevated $\delta^{15}N$ as a criterion, Shahack-Gross and Finkelstein (2008) were able to identify specific deposits in the Iron Age site of Atar Haroa (Negev Highlands, Israel) as dung used for fuel.

Variation in soil $\delta^{15}N$ due to past site activities was shown to be reflected in modern plants growing on Norse sites on Greenland in a series of papers by Commisso and Nelson (2006, 2007, 2008, 2010). Sampling and analysis of plants on a range of sites showed systematically heavier nitrogen values in byres, (manured), infields, middens and (to a lesser extent) burial sites. In the latter case, the human consumption of seal meat may have contributed to the elevated $\delta^{15}N$ values (see Makarewicz and Sealy, 2015 for discussion of ^{15}N use in archaeology).

The practice of manuring has also been approached by studying the $\delta^{15}N$ values in archaeological plant remains, especially cereals. Bogaard et al. (2007) tested wheat from long-running trial fields, comparing manured and non-manured plots. Grains as well as chaff from the manured plots showed significantly raised $\delta^{15}N$ values. Fraser et al. (2011) presented a more extensive study that compared various cereals and pulses from sites from across Europe and also from Syria (to include greater climatic variablility). Offsets in $\delta^{15}N$ values in the cereals were confirmed, but only in long-term manuring experiments. Apparently the effect needs to be built up by repeated manuring on the arable plot. However, a similar effect in pulses was only detectable under conditions of very intensive manuring. Kanstrup et al. (2014) studied the variation in $\delta^{15}N$ in charred cereal grains from the 4th to the 1st millennium BC. Changes in the nitrogen values were interpreted as representing a long-term decrease in manuring for emmer wheat (3900–500 BC) and an increase in manuring intensity for barley cropping (2300 BC–1 AD). However, Fiorentino et al. (2014) indicated that, although high $\delta^{15}N$ values in crops can be derived from high $\delta^{15}N$ sources like manure, they may also be linked to generic “rich” soils (i.e. with large and easily available nitrogen pools), in which manuring does not necessarily play a role. They stated that “overall, $\delta^{15}N$ may be used as an indicator of the nutrient status of ancient crops, having the potential to reflect both the effect of manuring and the overall nutrient quality of agricultural soils”.

For future research, it would be a step forwards if it was possible to resolve whether manuring was part of ancient cropping systems, or if $\delta^{15}N$ changes were caused by other agricultural changes, for example, soil nutrient depletion (causing decrease of $\delta^{15}N$) or cultivating previously fallow areas (increasing $\delta^{15}N$). One approach may be to systematically determine stable isotope characteristics of both the agricultural soil and the (charred) plant material derived from it, wherever this is possible.

Further developments in isotopic research are showing potential for providing climatic and hydrological information from the stable hydrogen isotope (D/H) ratios in biological materials (see Makarewicz and Sealy, 2015). Difficulties arising from mixing of sources with different fractionation histories have led researchers to focus on individual organic compounds rather than bulk organic matter. In particular, certain lipids from sedimentary terrestrial and aquatic organisms have δD values that are offset from, but highly correlated with, that of the water source used by these organisms (for discussion, see Terwilliger and Jacob, 2013; Sachse et al., 2012).

Terwilliger et al. (2013) analysed δD of land-plant derived fatty acids from Holocene soil sequences in the Horn of Africa. Data from these tests was combined with bulk carbon isotope and elemental analyses, charcoal identification, ^{14}C dating, image analysis of soil thin sections to distinguish charred organic matter, soil physical descriptions and organic matter quality tests. Through this multiproxy study, the authors concluded that δD from soil sequences reflected changes in rainfall which themselves correlated with the rise and fall of two civilizations in the region.

4. Taphonomy and Preservation

4.1. Taphonomy

Taphonomy is an umbrella term which touches on most areas of our discussion and many others in this special issue. Some decay processes are discussed under Preservation in situ (below) and some mineralisations under Cave sediment diagenesis (above). However, there are a few scientific advances in taphonomic analysis that fall outside the major headings. It is critical to the future of archaeological science that they continue to appear, even where they apply to only a small set of circumstances, as it is through these building blocks that the larger picture gradually emerges. Well-known cases are preservation by salt at Hallstatt, Austria (Barth and Lobisser, 2002) and by copper, e.g. at Alderley Edge, UK (Smith et al., 2011).

The effects of reduction on the decay of organic remains is another area of interest. Some of the most extraordinary examples came from the South Scandinavian barrows, where wet inner cores to the barrows were maintained in some cases by an encapsulation of solid iron pans formed as a result of prolonged reduction (Breuning-Madsen and Holst, 1998). Experimental work, involving deliberate burial of fresh meat under similar conditions showed that it was possible to prevent decay almost completely for three years (Breuning-Madsen et al., 2001).

In some situations, particularly where stratigraphy associated with middens is slightly acidic and high in phosphorus, biological material can end up preserved by phosphatisation. Biases in the species and plant parts phosphatised at Potterne, UK were attributed principally to the original tissue's lignin content and robustness (McCobb et al., 2003). At the microscopic scale, crystallisation of phosphate can be weakly expressed, which makes characterisation difficult. Adderley et al. (2004) examined faintly anisotropic Ca–Fe-phosphate pore infills in micromorphological thin sections from an early fishing site at Langenesværet (Norway) using synchotron X-ray scattering. Nano-scale crystalline properties of the infills showed strong similarities with reference fish material, supporting original evidence from PIXE analyses suggesting that the infills were derived from fish bone.

4.2. Preservation in situ

The development and signing of the 1992 Malta convention (also known as the Valletta convention) played a major role in the emergence of preservation in situ as a new area of study within archaeology and (especially) geoarchaeology. This convention obliges all countries who signed it amongst other things to "*implement measures for the physical protection of the archaeological heritage*" (Council of Europe (1992)). It also made necessary the prediction of future degradation processes and potential mitigating measures. Three main branches of study developed in the newly emerging research area: Processes of Decay, Site Degradation and Monitoring.

4.2.1. Processes of decay

4.2.1.1. Wood. Various studies have characterised decay processes and the role of the burial environment (see Huisman, 2009a; Matthiesen, in press), and many detailed works have examined individual materials. A lot of this research has focused on the decay of archaeological wood. General knowledge on microbial wood decay was gathered by Blanchette (2000), showing how fungi (white-rot, brown-rot and soft-rot) and several types of wood-degrading bacteria (including erosion-bacteria) are related to specific environments, and produce distinct degradation patterns. He also indicated that archaeological wood virtually always shows some form of microbial degradation, most commonly soft rot fungi in terrestrial settings and erosion bacteria in waterlogged sites. Huisman (2009a) states that erosion bacteria do not fully degrade wood, but only attack the secondary cell wall. Their activity causes wood to become soft, to have a higher water content and to become damaged when it dries out. However, in contrast to the fungal decay processes, full destruction of the wood does not occur. Björdal and Nilsson (2002) showed that white-rot fungi may also colonise and degrade archaeological wood when wetlands are severely drained. Huisman and Theunissen (2008), however, working at the New Dordrecht peat trackway (The Netherlands), demonstrated that penetration of oxygen is not enough to trigger fungal decay as long as the wood remains fully waterlogged. This is corroborated by Milner et al. (2011), whose SEM-images of decayed wood from Star Carr (UK) show only evidence for decay by erosion bacteria.

Extensive research on decay of waterlogged wood by erosion bacteria was later published by several authors (see Klaassen et al., 2008). Huisman et al. (2008a) demonstrate that evidence of decay by erosion bacteria can be found in archaeological wood in a range of waterlogged burial environments, including iron- and sulphate-reducing conditions. Klaassen (2008a, b) in a study on wooden foundation piles, argues that the extent of degradation by erosion bacteria is related to the flow of water through the wood vessels. Kretschmar et al. (2008) and Gelbrich et al. (2012) showed that erosion bacteria can degrade wood in the absence of oxygen, and that low nitrogen availability increases the intensity, whereas increased sulphate levels decrease it, probably because of the formation of toxic sulphides. Filley et al. (2001) showed that, for soft-rot fungi, increased wood decay in a burial site known as "Midas' tomb" is related to increased nutrient levels originating from decay products of a human body and buried food gifts. Björdal et al. (2012) studied the environment under which marine borers (like the shipworm) degrade wood from shipwrecks, and how low temperature and oxygen levels - as found, for example, in the Baltic – may protect marine underwater sites.

4.2.1.2. Bone. Several studies targeted the decay mechanisms and the relation to the burial environment of archaeological bone. In laboratory studies of the pure chemistry, Berna et al. (2004) showed that bone is likely to be best preserved in sediments with a pore solution pH above 8.1, i.e. saturated with respect to calcite. In alkaline to neutral conditions, bone mineral undergoes recrystallization into authigenic apatite. This process will be more intense as the pH approaches neutrality, and below pH 7.5, the original bone mineral will be totally replaced by authigenic apatite. In the field, however, microbial decay is extremely important in archaeological bone degradation processes (Hedges et al., 1995). Jans et al. (2004), in an extensive histological study of decay patterns in 261 bones from 41 sites throughout Europe, found evidence of chemical transformation resulting in a loss of collagen and alterations to the mineral phases in 12% of the bones (see also Smith et al., 2002). In 87% of the other bones, evidence for microbial decay was found. Bacterial alteration was most common in bones from humans and animals buried as a whole, indicating that this type of decay is mostly restricted to putrefaction processes. Fungal decay – recognizable by its typical Wedl tunnelling – occurs only in specific burial environments, and is usually absent in calcareous, permanently frozen or desert environments (see also Huisman, 2009a). Turner-Walker (2009), Milner et al. (2011) and Boreham et al. (2011) showed that acidification caused by pyrite oxidation in drained peatland results in dissolution of the mineral component. The remaining collagen gives the bones from such sites more elastic properties and complicates their recovery and conservation.

4.2.1.3. Metal. The corrosion of metals has already been studied extensively (e.g. Evans, 1960; Western, 1972). However, a new approach was developed by Matthiesen et al. (2004), who combined X-radiography and a GIS approach to document the degree of corrosion of metal objects from the Nydam Mose (Denmark) weapon hoard, and link it to the depth of burial and the burial environment. They came to the conclusion that the corrosion on these objects had occurred shortly after burial, and that the process was more or less dormant after that. This was confirmed in

Matthiesen et al. (2007) when field tests with buried fresh metal coupons showed very fast corrosion rates.

4.2.1.4. Glass. Huisman et al. (2008b) researched the processes that cause some types of colourless Roman glass to disintegrate in situ, resulting in minute articulated glass fragments, colloquially known as “sugar glass”. They demonstrated that this type of glass was made with lower concentrations of calcium than normal soda-silica-lime glass, which is rarely affected by leaching. They argue that this allows extensive leaching of the glass, which in combination with fluctuating soil moisture levels, causes thin-walled glass to fragment and thick-walled glass to disintegrate completely.

4.2.2. Site Degradation

Others studied degradation processes that affect complete sites instead of single material categories. Cederlund (2004) and Pascoe (2012) used side-scan or multibeam sonar to study erosion processes on submerged archaeological sites. Quinn (2006) investigated erosion patterns that typically occur around shipwrecks. On land-based sites, an especially innovative method to study and quantify modern erosion rates made use of ^{137}Cs distributions (Wilkinson et al., 2006). Very topical is the research by Elberling et al. (2011), Hollesen et al. (2012) and Matthiesen et al. (2014) who showed how a warming climate may cause extremely well preserved archaeological remains in permafrost to thaw and quickly deteriorate.

The impact of construction processes on archaeological sites also received attention (see Huisman, 2012). Huisman et al. (2011) and Williams et al. (2008) used field tests and scaled-down laboratory tests to assess the damage done to archaeological sites by driven piles. Williams et al. (2008) showed extensive down-pull of layers in simulated sandy material. Huisman et al. (2011), however, found that damage by piling through shallow clay and peat layers outside the pile diameter is often negligible.

Some researchers applied spatial and processual modelling to predict degradation of archaeological remains. Crow (2008) related mineral weathering and groundwater composition to processes and rates of dissolution of archaeological inorganic materials. Chapman and Cheetham (2002) used relatively simple spatial hydrogeological modelling to predict degradation of archaeological remains.

4.2.3. Monitoring

At the site level, several methods and techniques have been developed for monitoring archaeological sites. They have the basic premise in common that key properties of the site need to be determined repeatedly. Properties may be related to the burial environment, may give an estimation of the state of degradation of archaeological remains or may be indicators for active degradation processes (Smit et al., 2006; Huisman, 2009a).

4.2.3.1. Monitoring techniques. One approach is to characterise (changes in) the burial environment. Many of these studies focus on wetlands, and employ various methods for monitoring e.g. water dynamics, oxygen penetration, redox potential, pH etc. (cf. Smit et al., 2006; Huisman, 2009a). A second approach – used less often – is to focus on the quality of specific archaeological materials that were recovered from the sites with minimally invasive methods. van Heeringen and Theunissen (2002, 2004) and Jones et al. (2007) developed standard methods to assess the state of preservation of botanical remains. Finally, several studies investigate or monitor whether specific degradation processes are active. In Cederlund (2004), fresh wood samples were positioned at submerged marine archaeological sites in order to assess whether degradation by microbes or shipworms was active. Gregory et al. (2009) also used modern wood samples as a proxy to study wood degradation. Matthiesen et al. (2007) used metal coupons to study degradation processes in Nydam Mose. Huisman (2009b) argues that soil micromorphology is well suited to study which processes are active in the burial environment, focussing on redox-sensitive minerals, organic matter properties and soil structure.

There has been a large variation in which techniques were used for monitoring programmes. For example, Lillie et al. (2008) monitored several Scottish Crannog sites for a little over one year using groundwater levels, redox conditions and pH as parameters. Jones and Bell (2012) report a c. 1½ year period monitoring those same parameters, but also soil moisture content, major-element water chemistry and conductivity at the Glastonbury Lake Village and Somerset levels sites (UK). Based on the water dynamics, they indicate that the sites are under threat from desiccation. In both cases, however, the monitoring was not continued. Other sites have been monitored repeatedly. For example the UNESCO heritage site of Schokland (Netherlands) has seen three monitoring rounds in 15 years employing not only chemical parameters, but also large datasets of high-frequency groundwater data, studies of botanical remains, bone fragments and micromorphology. This study benefited greatly from increased availability of groundwater monitoring data (van Heeringen et al., 2004; Huisman and Mauro, 2012, 2013).

At the UNESCO world heritage site of Bryggen (Norway), a combination of approaches is being used. Extensive monitoring and assessment using groundwater levels and composition, along with soil characteristics is combined with elaborate modelling of hydrogeology, hydrochemistry and decay of organic materials in order to predict and prevent decay (e.g. De Beer et al., 2012; Hollesen and Matthiesen, in press; Matthiesen, 2008).

Some aspects of monitoring remain controversial. Williams (2012) and Huisman and van Os (2014) argued that many monitoring programmes have no practical foundation (e.g. there is often no plan or budget for intervention if results are negative). Moreover, van Os et al. (2012) thought that monitoring programmes in many cases are unnecessarily complex and technological. For example in core profiles, macroscopical observations of soil colour – and sometimes smell - suffice for determining the depth of oxygen penetration without the need for redox probes or complex oxygen measurements.

In the future, it is likely that there will be trend towards lower-tech and simpler techniques for site assessment and monitoring. At the same time, increases in widely available relevant data – including elevation models and groundwater levels may make more elaborate modelling at specific key sites feasible.

5. The Longer Term Outlook

The studies discussed above represent only a part of the range of earth science applications in archaeology. As with other branches of science, small changes in methodology can lead to disproportionately large advances in the scientific understanding derived from them. Approaches that remain relatively static, although not featuring in this discussion, may nevertheless be regularly providing valuable interpretative information at a site level. Futures sections, dealing with possible study directions, can be found at the end of the discussions above, where appropriate. We want now to look at the bigger picture of directions for the development of geoarchaeology.

For environmental histories, as techniques become more and more complex, we need to see greater validation from the use of multi-proxy studies. In our section on land-use, vegetation and climatic studies (above), we initially highlighted micromorphological, phosphate and palynological studies; these gradually involved additional carbon isotope approaches, and, coming up to the most recent examples, we see the possibilities of using nitrogen and hydrogen isotopes as well. The newer techniques often reflect the latest instrument capabilities (e.g. deuterium/hydrogen measured in particular lipids). This does not mean they are better techniques, but it does mean that new technology and understanding can produce overlays which automatically check and control the interpretations from the earlier approaches.

Multi-proxy validation is particularly needed in developer-funded archaeology, where site directors may have limited scientific knowledge, but are having to judge the value of a technique offered to them commercially by that technique's proponent. It is not only the complex techniques that can cause problems. Fear of misuse in the commercial sector is also probably a major source of the often-heard expressions of caution concerning pXRF (see discussion under Phosphate and multi-element soil analyses above). In a media driven age, new techniques can easily become over-exposed in an initial euphoria, only to find themselves widely discredited when the answers turn out to be less clear than was originally hoped (see Pollard, 2011). In so many cases, the problems can be boiled down to asking the right questions, both significant to the archaeology and appropriate to the level of accuracy the equipment can give.

This brings us to the importance of education. Being able to ask the right questions arises from an understanding of the scientific method, not necessarily an understanding of each individual technique. Without the integration of science into archaeological teaching, there is a real danger of promoting an intellectual schism in archaeology along the classical arts/science divide. This has become a particular problem in the U.S. where large numbers of archaeologists receive their degrees without any compulsory science training and where, amongst those universities who offer such training, voluntary uptake is low (Killick and Goldberg, 2009). Shackley (2010) felt that this division and the scientific ignorance it promoted, was the crux of the problem with wholesale acceptance of pXRF in archaeology.

The various strands of science we call geoarchaeology sit squarely in the middle of this issue, since site formation processes are a large part of the analytical work, and are so fundamental to the interpretation of most sites. Ultimately, practitioners of geoarchaeology need to make sure that the scientific approach underpins not only the methods, but the questions asked of those methods.

6. Conclusion

The tremendous growth of both knowledge and application which has characterised the various parts of geoarchaeology in the last twenty years has been matched by a sea-change in scientific rigour, resulting in a more detailed understanding of the multitude of processes which, together, form archaeological stratigraphy and determine its change over time. This scientific approach must continue to flourish, both through exemplary analytical work and through educating the next generation of researchers. An important component of this growing success is the confidence that comes from validation through experimentation and multi-proxy studies.

Broadly speaking, we foresee similar developments continuing over the *next* twenty years mainly in the methodologies represented here, probably as well as some we cannot yet foresee. This is very much to be welcomed, with only the mild proviso that they should not, in the pursuit of detail, lose sight of their original purpose. Applicability to archaeological investigation must remain the heart and soul of the project.

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