Bat guano and preservation of archaeological remains in cave sites

Ruth Shahack-Gross\textsuperscript{a,}*, Francesco Berna\textsuperscript{a}, Panagiotis Karkanas\textsuperscript{b}, Steve Weiner\textsuperscript{a}

\textsuperscript{a}Department of Structural Biology, Weizmann Institute of Science, Rehovot 76100, Israel
\textsuperscript{b}Ephoreia of Paleoanthropology-Speleology, 34b Ardittou, Athens 11636, Greece

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Abstract

The formation of authigenic minerals in cave sediments can be used to reconstruct the paleochemical conditions that prevailed in the past, and in this way to assess the completeness of the archaeological record. Previous studies indicated that the major driving mechanisms for chemical diagenesis in prehistoric caves that result in the formation of authigenic minerals, are the degradation of bat guano and the local hydrology. We therefore investigated contemporary bat guano deposits in caves and the sediments directly below such deposits. The emerging patterns show that the formation of authigenic minerals occurs under acidic conditions within tens of years. The availability of phosphate, Al, K, and Fe increases with increasing organic matter degradation, while the availability of nitrogen and sulfur decreases. Insectivorous bat guano contains larger amounts of phosphate and is more acidic than fruit bat guano. In the first stages of diagenesis micro-chemical environments form within the degrading bat guano that result in the formation of a wide variety of authigenic minerals. During advanced stages of diagenesis steady state conditions are achieved resulting in authigenic mineral assemblages being dominated by one mineral type at the same locale. This is reminiscent of known distributions of authigenic minerals in prehistoric cave sediments. Under the acidic conditions produced by degrading bat guano deposits, calcareous artifacts and bones are not expected to persist for long periods of time, unless there is a lot of calcite in the sediments that could buffer the sediment water pH. Guano itself is not likely to be preserved. Periods of cave abandonment can be inferred from the presence of authigenic minerals in the sediments as it is during these times that bats mainly occupy the cave. The occurrence of certain authigenic minerals in open-air sites may serve as evidence for areas rich in organic matter containing phosphate (i.e., animal enclosures, latrines, sewers, trash pits) and/or bones. As the degradation process is rapid, the use of authigenic minerals to identify these loci is relevant to almost all archaeological, as well as historical sites.

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1. Introduction

Human occupation of caves is inferred from the presence of artifacts in the sediments or on cave walls. The absence of artifacts however cannot be regarded as an absence of human occupation because post-depositional diagenetic processes may alter the anthropogenic signatures. Chemical processes, for example, may affect mineral artifacts (e.g., bones, flint, and others) causing partial or total dissolution, or change the artifact into another mineral type [8,12,14,22,24,32]. In order to determine whether mineral artifacts were deposited at a site, but subsequently dissolved, it is necessary to reconstruct the paleo-chemistry of the archaeological sediments. Karkanas et al. [13] proposed that such a reconstruction is possible if authigenic minerals (i.e., secondary minerals) form in the sediments shortly after deposition. Because these minerals form under defined chemical conditions, they essentially “record” the chemical environment in the sediments.

Phosphate minerals are among the most common authigenic minerals that form in caves because they mainly originate from the degradation of bat guano [9,10]. Little is known, however, about the chemical conditions that determine their formation, the time scale of their formation in degrading bat guano, and about
the manner in which degrading bat guano affects the archaeological record of caves. This is the focus of the present study. We have conducted a mineralogical and geochemical study of contemporary bat guano deposits and the underlying sediments in six caves in Israel.

1.1. Bats and bat guano

Bats live all over the world in temperate and tropical environments. Social species form aggregates of considerable numbers (up to several millions) in caves or abandoned structures. Reported rates of guano deposition vary between 2 and 10 cm per year [10]. In Israel there are at least 32 species of bats, 31 are insectivorous and one is frugivorous [16]. The earliest remains of insectivorous bats in Israel are from the Pleistocene, found as fossils in the Ubeidiya Formation (Jordan Valley) dated to ca. 1.4 My [29]. A study on the feeding habits of 4 insectivorous bat species in northern Israel shows that beetles (Coleoptera) are a major source of food [35]. The earliest remains of frugivorous bats in Israel are from Kebara Cave (Mount Carmel), with fossil remains of Rousettus aegyptiacus dating to ca. 16,000 BP [29]. A study of the feeding habits of R. aegyptiacus in northern Israel shows that 87% of its diet is based on fruit, mostly of the genus Ficus (figs and their relatives) and the remaining 13% is composed of leaves and pollen [16].

Chemical analyses of three samples of fresh bat guano, two of insectivorous species and one of a possibly frugivorous species show that weight loss on ignition is between 83 and 94%, which is mostly due to water and organic matter [10]. The most abundant elements in these samples are nitrogen and phosphorous, where total N ranges between 8 and 12% and P ranges between 2 and 7%. Other elements (Ca, Mg, K, Al, Fe, and S) are present in quantities lower than 5% each [10]. Upon ashing, P comprises more than a third of the ash (36–43%) and N is 9–14%. The acid insoluble fraction of the ashed guano is about 1% of the fresh droppings [10]. One analysis of bird guano in a cave shows that it is composed of about 4% of N and 7% of P; values that are in the same range as bat guano [10].

The minerals found in profiles of degraded bat guano include Ca phosphates in upper parts of profiles and Al or Fe phosphates in lower parts of profiles [9,10]. The source of the Ca is from carbonatic rocks, namely from cave walls and the ceiling, whereas the source of Fe and Al is from the interaction of phosphate and clays that results in the breakdown of the latter [9,21].

1.2. Degradation of organic rich bat guano deposits

No specific studies of degradation of bat guano are available. Studies of organic matter decomposition can be used as guidelines for understanding decomposing bat guano. In general, the most abundant organisms in soils that contribute to organic matter decomposition are bacteria and fungi [1]. The major waste products of microbial growth are CO₂, CH₄, organic acids such as acetic and formic acids, and alcohol [1]. Several bacteria are able to oxidize elemental sulfur, forming sulfuric acid and can thus cause a decrease in soil pH usually to values around 4.0 and even lower [1,20]. These are important agents in chemical diagenesis. Bacterial processes also result in the formation and accumulation of nitrate and sulfate salts [1,9,20].

The strategy used in this study is to correlate empirical data of authigenic minerals found in contemporary decomposing bat guano sediments in caves, with the pH, phosphate content and organic matter content of these sediments. This provides a basis for better understanding the driving mechanisms of chemical diagenesis and the impact of chemical diagenesis on the archaeological record of prehistoric caves, as well as organic-rich areas of open-air sites.

2. Materials and methods

2.1. Reference material

Fresh and slightly decomposed bat guano was sampled in four caves (Kebara, Hayonim, Ornit, Hazorea) and one underground shelter (Beit-Yosef) in Israel, currently or recently occupied by bats. Guano of fruit bats was collected in Kebara and Hayonim caves, and guano of insectivorous bats was collected near Beit-Yosef (Jordan Valley, species Asellia tridens) and near Hazorea (Jezreel Valley, species Myotis capaccini bureschi) (Fig. 1). Pigeon guano was collected in two caves (Kebara, Hayonim) (Fig. 1).

2.2. Sediment profiles

Fieldwork was conducted in three caves located on Mount Carmel, northwestern Israel (Kebara, Ornit, Etzba; Fig. 1).

Kebara Cave, known for its prehistoric remains, has not been excavated since 1989 and is currently inhabited by a large colony of fruit bats (R. aegyptiacus). Sediments were sampled close to the rear wall of the cave; an area that was excavated in 1931 by F. Turville-Petre that reached dry, red-colored archaeological deposits containing Aurignacian (Upper Paleolithic) artifacts [2]. Thus bat guano has accumulated in this area and interacted with archaeological sediments for the last 70 years. The area was lightly cleaned of guano deposits in the early 1980s before the excavations led by O. Bar-Yosef, and was last cleaned in 1993 (O. Bar-Yosef, pers. comm., 2003). Pigeons also inhabit the cave.
Ornit Cave is less accessible to humans, and is seasonally (from November to March) inhabited by two insectivorous bat species (*Rhinolophus hipposideros minimus* and *Myotis* sp.). The sediment samples were obtained from a completely dark chamber in the back of the cave that has only a small access tunnel. To our knowledge it was never excavated. We did find a few flint artifacts and some pottery.

Etzba Cave was occupied by an unknown species of insectivorous bats until at least a decade ago. The sediment samples were obtained from a side chamber, known to have been occupied by bats, abutting a large chamber that is completely dark.

### 2.3. Fieldwork

Test pits were opened in all locations, measuring about 0.5 m\(^2\). The depth of each pit was determined by locating the contact between the guano deposits and bedrock or organic-poor sediments. The open sections/profiles were photographed and sampled according to the visible stratigraphy, based primarily on color differences. Loose sediment samples were collected from each stratigraphic unit and placed in glass vials. They were used for bulk analyses. In addition, undisturbed samples of the whole sediment profile, in the form of rectangular blocks, were collected and tightly wrapped in paper and then masking tape. These samples were used for micromorphological examination. Note that two or more pits were opened at each locality, even though the detailed analyses reported here may be for only one.

### 2.4. Micromorphology

Embedded block samples were prepared following conventional procedures (e.g., [5]). Thin sections were prepared by Spectrum Petrographics Ltd. (Winston, Oregon) and analyzed using a Nikon polarizing light microscope (Labophot2-pol). Descriptions follow Bullock et al. [4] and Courty et al. [5].

### 2.5. Mineralogy

Mineralogical analyses of bulk samples were made using Fourier Transform Infrared (FTIR) spectroscopy (MIDAC Corp., Costa Mesa, CA, USA). Spectra were obtained by mixing about 0.1 mg of powdered sample with about 80 mg of KBr. Spectra were collected at 4 cm\(^{-1}\) resolution (for more details see [32]). In addition, uncovered thin sections or embedded blocks were polished and prepared for Energy Dispersive X-ray spectrometry (EDS) analyses. The polished samples were carbon coated and analyzed with a Jeol 6400 scanning electron microscope with an EDS Link (Oxford Instruments) operating system. Elemental analyses were performed in order to identify the various minerals based on stoichiometry (phosphate minerals cannot be easily distinguished using petrographic...
2.6. Chemical analyses

Samples of fresh bat and pigeon guano were homogenized using a mortar and pestle. The large amount of organic matter in these samples resulted in an uneven homogenization. The homogenized sediment was therefore sieved through a 0.5 mm sieve and the fraction smaller than 0.5 mm was taken for analysis. The samples were analyzed for phosphate content, organic matter content, and pH (described below). In addition, the samples were ashed in an oven at 550 °C for 4 h and weighed. Aliquots of these ashed samples were dissolved in 1 N HCl. The acid insoluble fraction (AIF) was rinsed and weighed. Aliquots of these ashed samples were dissolved in 1 N HCl. The acid insoluble fraction (AIF) was rinsed and weighed. The homogenized sediment samples were analyzed for phosphate content, organic matter content, and pH (described below). In addition, the samples were ashed in an oven at 550 °C for 4 h and weighed. Aliquots of these ashed samples were dissolved in 1 N HCl. The acid insoluble fraction (AIF) was rinsed and weighed.

Bulk sediment samples were homogenized using a mortar and pestle. The pH of homogenized samples was measured using a pH-meter (Metrohm 654) after preparation of saturated solutions in water [30]. The weight percent of PO₄ was determined colorimetrically using the ascorbic acid method [19]. Samples were ashed in a furnace oven at 550 °C for 30 min, and the solution was stirred occasionally. The solution and insoluble fraction were washed with 20 ml DDW into 50 ml measuring bottles, and filled up. The solution was further diluted 1:100 and prepared for the colorimetric measurement using the phosphomolibdic blue color assay and an LKB Biochrom, Ultraspec II, 4050 UV/Visible spectrophotometer at 700 nm wavelength. In addition, samples were analyzed for organic matter content (weight %) thermogravimetrically. Samples of about 10 mg were placed in a simultaneous DTA-TG chamber (DTG-50, Shimadzu, Japan) and heated to 1000 °C in air at 20 °C/min. The weight loss due to organic matter oxidation was measured between 200 and 600 °C. This range was chosen in order to exclude weight loss due to water evaporation (at temperatures below 200 °C) or mineral transformations (at temperatures below 200 °C, e.g. structural water of gypsum, and above 600 °C). In one instance (sample BYN-1) the DT signal showed significant weight loss until about 700 °C. Thus weight loss was calculated for that sample between 250 and 750 °C.

3. Results

We present the results by sites, starting with the description of the stratigraphy based on field and micromorphological observations, and continuing with results of mineralogy (based on FTIR, micromorphology and EDS), phosphate content, organic matter content, and where applicable, ash composition.

3.1. Fresh guano

3.1.1. Fruit bat guano

Fresh guano of fruit bats is dark and forms a flat, laminated mass. It generally contains more than 60% organic matter (Table 1). It is composed mainly of cellulose, and the most abundant mineral in the fresh guano is clay. Some quartz and traces of dolomite or calcite may also be present. These minerals are probably derived from dust either adhering to the eaten fruit or blown onto the guano shortly after its deposition. The pH of fresh fruit bat guano is near neutral to alkaline, and its phosphate content ranges between 5.1 and 7.7% by weight (Table 1). The ash of fresh fruit bat guano is composed mostly of calcite, and smaller amounts of clay and quartz, dahllite and ammonium sulfate. The calcite is probably formed from plant calcium oxalates during the ashing (Table 1).

3.1.2. Insectivorous bat guano

Fresh guano of insectivorous bats is dark, composed of small fecal pellets that form an aggregated mass. With degradation it becomes gray-colored and powdery. Its organic matter content ranges between 53 and 65% by weight (Table 1). It is composed mainly of chitin and traces of clay. The authigenic mineral brushte (CaHPO₄·2H₂O) was identified in fresh pellets in the form of microscopic crystals. The pH of fresh insectivorous bat guano is slightly acidic, and its phosphate content ranges between 25 and 57% by weight (Table 1). The ash of fresh insectivorous bat guano is composed of an as yet unidentified phosphate mineral and ammonium sulfate (Table 1).

3.1.3. Pigeon guano

Fresh pigeon droppings are light, including white, green, yellow, orange and brown colors, in a spiral form. It contains more than 60% organic matter. It is composed mainly of cellulose and contains nitratite (NaNO₃), calcite and probably clay. Its pH is near neutral to alkaline, and its phosphate content is around 10% by weight (Table 1). The ash of pigeon guano is composed of calcite, ammonium sulfate, dahllite, clay and quartz (Table 1).

3.2. Kebara Cave

Kebara Cave is currently inhabited by a colony of fruit bats. Test pits were opened near the edge of the excavated area. A 2–3 cm thick dark brown layer was observed in the upper part of the section, representing the organic rich guano. This organic sediment contains
sparse dung spherulites and dolomite crystals. The latter probably originate from the cave walls. The organic matter is mostly composed of cellulose degraded to varying degrees, and the structure of this layer observed in thin section is platy, with horizontal voids. The organic rich layer overlies firm clay-rich sediment that is characterized by white nodules and filaments of varying sizes and shapes (Fig. 2a). These features are most abundant in the 10 cm directly below the guano layer. They are composed of gypsum and dahlite. Horizontal gypsum veins occur directly below the guano layer, where the microstructure of the clayey sediment is platy. Below this horizon, the sediment becomes granular due to the action of soil fauna (i.e., bioturbation; evidence is found in the form of earthworm casts). In this granular sediment secondary gypsum occurs as nodules rather than veins, and nodules of dahlite are also present. Dolomitic rocks that had fallen from the cave ceiling and/or walls are embedded in the sediment and have dahlite reaction rims. By reaction rim we refer to the products of chemical reactions that take place on the

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Fresh guano samples from Kebara and Hayonim caves and Beit-Yosef underground shelter, indicating the minerals found in the fresh material and its ash, P má concentration, organic matter content, pH, and the acid insoluble fraction of the ashed material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source material</td>
<td>Sample number</td>
</tr>
<tr>
<td>Fruit bat guano</td>
<td>FKB-1</td>
</tr>
<tr>
<td>HYG-1</td>
<td>Calcite, clay</td>
</tr>
<tr>
<td>Insectivorous bat guano</td>
<td>BYN</td>
</tr>
<tr>
<td>MYO</td>
<td>Brushite, nitratite, ardealite, tamarakite</td>
</tr>
<tr>
<td>Pigeon guano</td>
<td>FKB-8</td>
</tr>
<tr>
<td>HYG-2</td>
<td>Nitratite, calcite</td>
</tr>
</tbody>
</table>

a Ammonium sulfate. b Weight loss calculated between 250 and 750 °C. c High value due to presence of authigenic phosphate minerals.

Fig. 2. Photographs of (a) representative sediment profile from Kebara Cave showing the occurrence of nodules below the organic rich guano layer. Smaller nodules occur in the organic rich sediment itself. The presence of nodules and concretions in organic rich and organic poor sediments associated with degraded bat guano was noted in all sediment profiles in this study. (b) Flatbed scan of a thin section of organic rich sediment from Section #4 in Ornit Cave, showing an oxidation front about 2 cm below the surface. The sediment above contains gypsum and phosphate minerals and has vertical desiccation cracks. The uppermost part contains small fragments of limestone and is impregnated by calcite. The sediment below the oxidation front is organic rich and contains smaller and fewer mineral nodules. (c) Flatbed scan of a thin section of a variscite concretion from Section #2 in Ornit Cave. The dark rim is clayey. Some of the light granules in the concretion are composed of tinsleyite and/or tamarakite. (d) Flatbed scan of a thin section of Section #3 in Ornit Cave showing thick tamarakite veins in a clayey groundmass.
outer surface of rocks buried in sediments [32]. A few bones were also observed in thin section. They seem to lose their distinctive Haversian (osteonal) structure. Note that dahllite nodules were found deeper in the section than gypsum nodules.

The authigenic (secondary) minerals found in the Kebara Cave section are nitratite (NaNO$_3$), gypsum and dahllite (Table 2). The pH along the profile ranges between 6.6 and 7.3, the phosphate content is lower than 5% by weight, and the percentage of organic matter ranges between 6.6 and 16.7% by weight, with the highest values at the top of the section, as expected (Table 2).

### 3.3. Etzba Cave

A colony of insectivorous bats inhabited the studied alcove 10 years prior to our sampling. No dark layers were macroscopically observed in profiles, but a thin layer (ca. 2 mm) rich in organic matter was observed about 2–3 cm below the present surface. The sediment above this layer is composed of finely laminated brown clay, and the sediment below is mottled with gray-white and brown domains. The gray-white domains are composed of calcite and/or limestone and the brown domains are clayey. The brown clay is impregnated to various degrees by secondary calcite. It follows that the main

<table>
<thead>
<tr>
<th>Location</th>
<th>Sample number</th>
<th>Depth below surface (cm)</th>
<th>Minerals (authigenic minerals in bold, secondary calcite underlined)</th>
<th>PO$_4$ (% by weight)</th>
<th>Organic matter (% by weight)</th>
<th>Acidity (pH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kebara Cave</td>
<td>FKB-203</td>
<td>1</td>
<td>Clay, dolomite, nitratite, dahllite, gypsum, quartz</td>
<td>1.0</td>
<td>16.7</td>
<td>7.0</td>
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<tr>
<td></td>
<td>FKB-204</td>
<td>4</td>
<td>Clay, dolomite, nitratite, dahllite, gypsum, quartz</td>
<td>u.d.$^a$</td>
<td>10.6</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td>FKB-205</td>
<td>12</td>
<td>Clay, dolomite, nitratite, dahllite, gypsum, quartz</td>
<td>4.6</td>
<td>7.8</td>
<td>7.2</td>
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<tr>
<td></td>
<td>FKB-206</td>
<td>20</td>
<td>Clay, dolomite, nitratite, dahllite, quartz</td>
<td>1.7</td>
<td>6.6</td>
<td>6.6</td>
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<tr>
<td>Etzba Cave</td>
<td>ME-23</td>
<td>3</td>
<td>Clay, calcite, nitratite</td>
<td>1.2</td>
<td>7.7</td>
<td>7.1</td>
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<td></td>
<td>ME-22</td>
<td>9</td>
<td>Clay, calcite, dahllite (trace)</td>
<td>2.1</td>
<td>5.3</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td>ME-21</td>
<td>15</td>
<td>Clay, calcite, dahllite (trace)</td>
<td>13.4</td>
<td>4.6</td>
<td>7.8</td>
</tr>
<tr>
<td></td>
<td>ME-20</td>
<td>24</td>
<td>Clay, calcite, dahllite (trace)</td>
<td>11.5</td>
<td>6.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Ornit Cave</td>
<td>MO-top</td>
<td>~1</td>
<td>Nitratite, gypsum, clay, ardealite</td>
<td>37.5</td>
<td>28.9</td>
<td>4.9</td>
</tr>
<tr>
<td>Organic-rich Section 1 (1/2002)</td>
<td>MO-middle</td>
<td>~5</td>
<td>Gypsum, ardealite</td>
<td>36.0±14.8</td>
<td>30.0</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>MO-bottom</td>
<td>~10</td>
<td>Nitratite, dahllite$^b$, gypsum, clay, taranakite,opal?; variscite</td>
<td>24.1</td>
<td>11.5</td>
<td>4.8</td>
</tr>
<tr>
<td>Section 4 (2/2003) (Same location as Section 1 but one year later)</td>
<td>MO-119a</td>
<td>0–2</td>
<td>Clay, calcite, dahllite$^b$, nitratite, ardealite</td>
<td>16.6</td>
<td>21.9</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>MO-119b</td>
<td>2–7</td>
<td>Ardealite, nitratite, gypsum</td>
<td>28.4</td>
<td>21.8</td>
<td>4.8</td>
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<tr>
<td></td>
<td>MO-119c</td>
<td>7–10</td>
<td>Ardealite, clay, nitratite, dahllite$^b$, taranakite</td>
<td>17.1</td>
<td>29.2</td>
<td>4.4</td>
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<tr>
<td>Section 3 (2/2003)</td>
<td>MO-111</td>
<td>0–1</td>
<td>Ardealite, nitratite, clay</td>
<td>11.9</td>
<td>38.6</td>
<td>4.6</td>
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<td></td>
<td>MO-112</td>
<td>4–5</td>
<td>Taranakite, highly crystalline dahllite$^b$, clay</td>
<td>23.7</td>
<td>5.7</td>
<td>5.4</td>
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<td></td>
<td>MO-113</td>
<td>10–11</td>
<td>Clay, dahllite$^b$</td>
<td>15.2</td>
<td>5.4</td>
<td>5.4</td>
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<tr>
<td>Section 2 (2/2003)</td>
<td>MO-100</td>
<td>0–1</td>
<td>Quartz, clay, variscite</td>
<td>24.2</td>
<td>6.3</td>
<td>6.1</td>
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<tr>
<td></td>
<td>MO-101</td>
<td>4–5</td>
<td>Altered clay (?), variscite, quartz, taranakite</td>
<td>29.2</td>
<td>7.7</td>
<td>4.5</td>
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<tr>
<td></td>
<td>MO-105</td>
<td>8–9</td>
<td>Altered clay, variscite, taranakite,opal (?), tinsleyite</td>
<td>22.9</td>
<td>9.1</td>
<td>4.1</td>
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<tr>
<td></td>
<td>MO-102</td>
<td>13–14</td>
<td>Altered clay, variscite,opal (?), tinsleyite</td>
<td>23.8</td>
<td>7.2</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>MO-103</td>
<td>17</td>
<td>Quartz, clay,opal, altered clay, variscite</td>
<td>5.9</td>
<td>16.3</td>
<td>4.2</td>
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<tr>
<td></td>
<td>MO-104</td>
<td>20</td>
<td>Altered clay, variscite</td>
<td>33.9</td>
<td>4.8</td>
<td>4.2</td>
</tr>
</tbody>
</table>

$^a$ Undetected.

$^b$ Dahllite probably associated with calcitic rocks (i.e., as a rock reaction rim).
diagenetic process is mobilization of CaCO$_3$ dissolved in drip water and formation of breccia. A few limestone rocks that had fallen from the cave ceiling and/or walls onto the surface and later buried in the section have reaction rims composed of dahlite. All along the profile there are discrete nodules of dahlite.

The authigenic minerals identified in the section are dahlite and nitratite (Table 2). The pH is near neutral to alkaline, the phosphate content is low in the upper levels and increases in the lower levels ranging between 1 and 13% by weight, and the percentage of organic matter ranges between 5 and 8% by weight (Table 2).

### 3.4. Ornith Cave

The studied chamber is seasonally inhabited by two insectivorous bat species. The four sections opened are all different and will thus be described separately. In all sections embedded limestone rocks have reaction rims composed of dahlite.

*Section #1* was opened in January 2002 in the center of the chamber. The 10 cm thick section is black from top to bottom and overlies what appears to be bedrock. The section contains many nodules of varying colors (white, gray and yellow) and sizes. It has a tightly packed microlaminated structure, indicating that there is little or no bioturbation by soil fauna. Thus degradation is mostly microbial. Various phosphate minerals are present in pores and voids, as well as large gypsum crystals (lozenge shaped). The authigenic minerals identified include nitratite, ardealite (CaHPO$_4$CaSO$_4$4H$_2$O), gypsum, dahlite, tarsanakite (H$_8$K$_2$Al$_5$(PO$_4$)$_8$18H$_2$O) and variscite (AlPO$_4$2H$_2$O) (Table 2). There is neither a clear segregation of mineral types along the profile, nor any indication of mineral replacement. Calcite fragments (i.e., bedrock) are present in low amounts in the uppermost few mm of the profile, probably derived from the cave ceiling and/or walls. The lowermost layer is a massive horizontal gypsum vein, probably indicating that the calcitic bedrock is a calcium source for both dahlite and gypsum. The section is further characterized by an acidic pH, high organic content, and high phosphate levels (Table 2).

*Section #4* was opened a year later adjacent to the first section. The upper 2 cm are clay-rich, black and firm. This layer contains small amounts of organic remains, calcite rock fragments, and is brecciated by calcite impregnation. The layer below is about 3 cm thick, composed of consolidated black sediment containing nodules of gypsum and phosphate minerals including ardealite, dahlite and tarsanakite, as well as nitratite. The lower layer is about 4 cm thick. It is a friable grayish sediment, dominated by organic matter, and is similar to the sediment described in Section #1 above (cf., MO-top and MO-middle with MO-119c, Table 2). It should be noted that the upper 4–5 cm also have vertical desiccation cracks. A comparison with adjacent Section #1 shows that in one year since the previous sampling the upper few centimeters of the guano-rich sediment decomposed and are now dominated by various mineral species. The border between the upper, highly mineralized layer, and the lower, still organic-rich layer, thus indicates an oxidation front (Fig. 2b). Note too that the uppermost layer has accumulated calcite from the ceiling and/or wall disintegration and precipitation from drip water. The section is acidic, has medium to high phosphate content, and high organic matter content (Table 2).

*Section #2* is located south of Sections #1 and #4. This section is about 20 cm thick. The uppermost cm is a clay-rich sediment consolidated by calcite impregnation. The next 3 cms are composed of fairly aggregated clayey sediment containing charcoal and pottery fragments, as well as large, homogeneous, concretions of phosphate minerals (Fig. 2c). These concretions are also found further down the profile and are composed mostly of varisite (AlPO$_4$2H$_2$O) with small amounts of tarsanakite, tinsleyite (K(Al, Fe)$_2$(PO$_4$)$_2$(OH)-2H$_2$O), clay, quartz, and possibly opal. The FTIR spectrum of the clay indicates that it is altered (see [33] for discussion on altered clay in cave sediments). The section is further characterized by near neutral pH at the top and acidic conditions from 4–5 cm depth to the bottom. It has a relatively low organic matter content and rather high phosphate content (Table 2).

*Section #3* was located under a boulder in the northwest corner of the chamber. The upper layer of this section is brown to black, organic rich and contains many nodules (yellow colored) of ardealite. This layer overlies 4 cm of nodular light colored sediment. It contains a criss-cross network of thick (up to 2 mm) veins of tarsanakite in a reddish groundmass of clay (Fig. 2d). This layer overlies an approximately 6 cm thick layer of red colored sediment (clay) containing white dahlite nodules, and a few pottery fragments. Note that the clay crystals are highly organized along the voids (i.e., a striated fabric). This may be a result of pedogenic clay illuviation, repeated wetting and drying, or may indicate clay alteration in the presence of large concentrations of phosphate. Clay alteration is consistent with EDS analyses which gave variable compositions that differ from montmorillonite and illite, the common clay minerals in the study area. The section is further characterized by acidic conditions, a low organic matter content layer that is associated with medium levels of phosphate, and a high organic matter content layer that is associated with a low phosphate content (Table 2).

### 4. Discussion

The six sections from three different caves show the effects of acids and phosphate released during bat guano...
degradation resulting in the formation of various authigenic minerals. This process occurs within a few years to tens of years. There is also a striking difference in the manner in which chemical diagenesis occurs in the sediments overlain by guano produced by fruit bats and that produced by insectivorous bats.

4.1. Fresh bat and pigeon guano

Based on the six fresh guano samples studied here, preliminary patterns emerge. Most striking is that insectivorous bat guano contains about 2–5 times more phosphate than fruit bat or pigeon guano, and the pH of fresh insectivorous bat guano is significantly lower than that of fresh fruit bat or pigeon guano. These differences will clearly influence the early diagenetic pathways of the underlying sediments. The differences in phosphate content reflect the diets of the bat species, namely mainly protein in insects vs. mainly sugars in fruit. Protein containing foods are richer in phosphorous than fruits [18].

4.2. Kebara Cave

The specific site chosen for analysis had accumulated large amounts of fruit bat guano in the last 70 years. The presence of arrays of nodules composed of authigenic gypsum and dahlomite more or less aligned with the surface shows that they must have formed during the last 70 years. The pH of the sediments is near neutral down to a depth of 12 cm, whereas that of fresh fruit bat guano is 7.7–8.0 (Table 2). The difference is presumably due to the release of acid from the degrading guano at the sediment surface. The phosphate content in the Kebara profile increases with depth, probably due to leaching out of phosphate from the organic-rich top sediment and its precipitation as rock reaction rims and/or nodules in lower parts of the section.

4.3. Etzba Cave

In Etzba Cave no bat guano was observed on the surface. The site was not inhabited by bat colonies in the 10 years prior to sampling. Thus all the guano had degraded completely in 10 years. Gypsum is absent in this section (cf., Kebara and Ornit caves), probably due to its dissolution in water. This is supported by the observations that the hydrological regime in the cave is quite active as evidenced from the accumulation of secondary calcite (by karstic activity) and the fact that water dripping was observed even when sampling in middle July (i.e., mid-summer). Note that the phosphate content in the Etzba profile (up to 13%) is higher than in the Kebara profile (up to 5%). The pH in the Etzba profile is more alkaline, thus favoring the formation and persistence of dahlomite. The difference between the sediments from Etzba and Ornit caves, both originating from insectivorous bat guano, is therefore due to different hydrological regimes (see below).

4.4. Ornit Cave

The four sections studied in Ornit Cave differ significantly from those in Kebara and Etzba caves, mainly with respect to the low pH of all the sediments, and the high phosphate content reflected in the presence of a suite of authigenic phosphate minerals (e.g., trenakite, variscite and ardealite). Authigenic opal and altered clays occur as well. The low pH is due to the waste products of the bacterial degradation acting on the insectivorous bat guano still present in this cave, that originally has lower pH values than fruit bat guano (Table 1). The authigenic phosphate minerals are a direct result of the interaction of the phosphate and various cations in the low pH environment within the cave sediments.

In Ornit Cave a marked difference exists between organic-rich and organic-poor sediments. Organic-rich sediments (22–39% organic matter) have a narrower pH range (4.4–5.2) than organic-poor sediments (5–16% organic matter, pH 4.1–6.1). In addition, organic-rich sediments contain more phosphate than organic-poor sediments (12–46% in the former vs. 6–34% in the latter), and their mineralogical suites are much more varied (Table 2). This implies that with organic matter degradation, changes occur in the pH regime, first towards acidic conditions but later towards more alkaline conditions. In addition, with degradation we expect the mineral assemblages to become dominated by one mineral. Such assemblages are often found in prehistoric caves (e.g., [14]).

Section #2 contains a suite of authigenic minerals that is dominated by one mineral (variscite), suggesting that in this section a pseudo-equilibrium or steady state has been reached. This notion is supported by the facts that this section has the lowest organic matter content and the widest pH range, showing that it has indeed been subjected to the most extensive breakdown of guano. The clays in the lower part of this section have all been altered, presumably due to the combination of low pH and phosphate adsorption [21]. Authigenic opal is present that may well be a consequence of clay breakdown [21]. The middle layer of Section #3 also appears to be close to a steady state condition as it is mostly composed of clay and trenakite. The other 2 sections are still organic-rich and contain a variety of authigenic minerals, one of which cannot form under only acidic conditions, namely dahlomite. It is stable above pH 7 [3]. In addition, they include rather soluble minerals such as ardealite, which contains both phosphate and sulfate, and is stable under acidic pH conditions [23], gypsum and nitratite. These sections appear to be in a state of transition. They still include local sources of calcium from the dissolving carbonate rocks in the section,
probably creating many micro-chemical environments. The concept of micro-environments in the sediments is further supported by petrographic microscopy and SEM imaging of the embedded sediments that revealed no clear order of formation of the phosphate minerals, and no clear evidence for dissolution of certain minerals and formation of others at their expense. The Ornit sections indicate that the chemical transition of sediments to a steady state involves the dissolution of gypsum, nitratite, ardealite and dahllite. All are absent from Section #2. Moreover, their dissolution most probably did not result in formation of other authigenic phosphate minerals as the phosphate content of organic-poor sediments is lower than that of organic-rich sediments (see above).

Below we present a synthesis of the results. This should be regarded as a working hypothesis until more data are available.

4.5. Synthesis

A plot of the pH and organic matter contents of the sediment and fresh guano samples for each of the caves (Fig. 3) shows that the Ornit sediments are well differentiated from those of Etzba and Kebara caves. In Ornit and to a more limited extent for Kebara and Etzba, the sediments (as opposed to the fresh guano) with higher organic contents have lower pH values. This appears to reflect the presence of still decomposing organic matter that is releasing acid. Once the organic matter content reaches a value around 5%, no more acid appears to be released, and the pH rises. Coupling these observations with the fresh bat guano analyses, we propose that the data reflect degradation pathways determined by the source organic matter and the local hydrological regime. Fig. 4 is a schematic diagram based on Fig. 3 that depicts the possible diagenetic pathways. The more common pathway is reflected in the sediments from both Kebara and Ornit caves. In both caves the pathways start with high amounts of organic matter in the fresh guano samples, but differ in pH values due to the difference in the source organic matter (i.e., fruit bat guano in Kebara and insectivorous bat guano in Ornit). In both pathways a decrease of about 1.5 pH units occurs, with the lowest values for degrading fruit bat guano reaching 6.6, and for degrading insectivorous bat guano reaching 4.2. This decrease in pH reflects
degradation processes of organic matter, as it is known that waste products of microbial degradation are mostly acids [1]. Based on the micromorphological observations of the upper few mm of sediment profiles from the caves, it seems that pH recovery is in part due to percolation of carbonate rich drip water that has a pH of 8.2. We thus chose to designate the end of this pathway in an area having about 5% organic matter and a pH of 8.2 (Fig. 4). In Etzba Cave, the pathway is different. The source material is insectivorous bat guano but instead of a decrease in pH we observed an increase (Fig. 4). Based on the micromorphological examination it is clear that the hydrological regime in the sampled chamber is highly active and the soil solution is saturated with respect to carbonate (i.e., formation of calcite breccia). The high content of carbonate in this system buffered the acid released during organic matter degradation. Note that this diagenetic pathway is situated within the general domain delineated by the diagenetic pathways of Kebara and Ornit caves. We assume that other pathways within this general domain are also possible.

Mineral formation follows organic matter degradation. Studies of authigenic minerals show that different minerals may form under specific chemical conditions. The combination of chemical parameters such as pH, phosphate concentration, aluminum concentration, potassium concentration, and redox potential, define the conditions under which a mineral is stable and will thus form [13,17,21,31]. Such sets of conditions are referred to as “mineral stability fields”. Once formed, some authigenic minerals will remain insoluble even if the conditions change, because the kinetics of the dissolution process may be very slow, especially when water is not abundant [21]. Fig. 5 (adapted from Fig. 3) shows the authigenic minerals found in the samples. The distributions of suites of authigenic minerals are encircled. Dahllite in the Ornit sections is excluded from Fig. 5 because it occurs mainly as reaction rims on carbonate rocks, and hence reflects only a very local microenvironment. The distributions of the minerals do roughly reflect their stability fields. Note that there are two major mineral suites that roughly correspond to the two main degradation pathways, one suite of low pH—high phosphate content (i.e., the Ornit pathway) and the second of high pH—low phosphate content (i.e., the Kebara pathway). Ardealite and brushite are clearly transition phases, formed while the organic matter is degrading. Gypsum and nitratite are found only in early stages of organic matter degradation when nitrate and sulfate accumulate due to microbial action, and are lost with time because these minerals are soluble in water. Taranakite has the widest stability field, forming in early stages of diagenesis and persisting into the mature sediments that reached steady state. Variscite, tinsleyite altered clay and authigenic opal represent later stages of diagenesis in insectivorous bat guano. Dahllite represents both early stages of diagenesis of fruit and insectivorous bat guano as well as later stages of diagenesis of fruit bat guano. It is conceivable that dahllite will form as an end product in mature sediments that underlay insectivorous bat guano, provided a phosphate source is available after the pH recovers. Such a source may conceivably be dissolving ardealite.

This study also shows which authigenic minerals may be preserved, but could be misleading in terms of paleochemical reconstructions. The highly insoluble authigenic minerals, such as taranakite, may persist for long periods of time, even though the conditions under which they form, may change. Taranakite dissolves so slowly that not enough time passes for it to dissolve completely. The presence of taranakite at a given location certainly implies that the pH at this location was once very low (and hence bones for example would have dissolved there), but does not imply that the pH remained low. In fact, measurements of pH in archaeological sediments containing taranakite from Kebara and Theopetra caves.
verified that the pH in most instances is near neutral and even alkaline (6.2–6.9 in Theopetra \(n=5\), and 3.7–8.2 in Kebara \(n=5\)). As pH increases due presumably to the buffering capacity of the carbonate system if the local rock is limestone or dolomite (Fig. 4), other authigenic phosphate minerals may form provided a source of phosphate is still available. This, in turn, is more likely to happen if such a layer is close to the surface, where both organic matter and water are available while deeply buried layers are not expected to undergo severe chemical changes.

We emphasize that water is a key agent in all the diagenetic processes we describe here. In dry climatic environments microbial activity is limited and little or no organic acid is produced. Thus the organic material itself may be preserved and more soluble authigenic minerals such as nitratite and gypsum may form and persist. Authigenic phosphate minerals are not likely to form in dry conditions [11]. We also note that in anaerobic environments such as organic rich water logged sites, the reduction in microbial activity will also change the diagenetic pathways.

This model should also be applicable to the effect of bird guano on underlying sediments, and in fact all organic matter that upon degradation releases acid and phosphate. The pH of the degrading material will depend upon the material being degraded (i.e., vegetal or animal), water availability, and the rate and kind of microbial degradation.

5. General and archaeological implications

This study provides information on the initial diagenetic events that take place in sediments that are exposed to the degradation products of organic materials rich in phosphate. Previous studies have focused on the mature sediments in prehistoric caves that were subjected to such changes some time in the past. These earlier studies showed how authigenic minerals, particularly the phosphate minerals, tend to occur in well-defined areas of the cave, and in some cases characterize the stratigraphy (e.g. Theopetra Cave; [12]). Their distributions correlate well with the presence or absence of bones in the sediment [14,28,32]. For example, it was shown that the occurrence of bones in Kebara and Hayonim caves correlate with the occurrence of dahllite in the sediments [32,33,34]. Knowledge of the stability fields of authigenic minerals can help reconstruct the paleo-chemical environment within the sediments. This in turn can be used to assess the completeness of the archaeological record of prehistoric caves (see e.g., [13,24,28,34]).

In this study we noted that all 6 sections analyzed were different, and even the 4 sections in Ornit cave that are all located within meters of each other are different. We concluded that during the first stages of diagenesis there are microenvironments within the sediment in which each mineral phase forms according to the local chemical conditions. These microenvironments form within tens of years following the onset of guano accumulation on the surface. The presence of these microenvironments is inconsistent with the general concept proposed by Karkanas et al. [13] that the authigenic minerals form as a reaction cascade, namely as the pH changes the authigenic mineral formation process tracks the changes. At least in the time scales of tens of years, the authigenic minerals seem to form de novo in appropriate local micro-chemical environments. With time however, the authigenic mineral suites do tend to reach a steady state, most probably through dissolution of the more soluble authigenic minerals (nitratite, gypsum, brushite, ardealite, and to some extent dahllite). This assertion is based on the observations of the organic-poor Section #2 from Ornit Cave that is dominated by one authigenic mineral type, and on the many observations in prehistoric caves of well defined spatial distributions of particular minerals. These mineral distributions are usually separated by boundaries that persist for long periods of time (e.g., Hayonim Cave; [33]).

The observations here of the very early stages of diagenesis in cave sediments reveal what is probably missing from the mature sedimentary record. What is clearly missing is the organic matter that is susceptible to microbial degradation, provided that it is not charred. In Etzba Cave all organic matter degraded within 10 years after the bats had left the cave. In abandoned pastoral sites in Kenya, large accumulations of organic matter (up to 1 m thick of animal dung) in livestock enclosures had completely degraded in a matter of 30 years after the sites were abandoned [25]. The relatively soluble authigenic minerals (nitratite, gypsum, brushite and ardealite) are also not expected to persist for long periods of time, if water is abundant. If these minerals are identified in mature archaeological sediments, their presence would indicate most unusual conditions of preservation.

This study shows that the authigenic minerals form in the sediments in a matter of tens of years. Similar time estimates for the formation of authigenic minerals in open-air pastoral sites in Kenya were reported by Shahack-Gross et al. [25]. This implies that the authigenic minerals that persist in the archaeological record (e.g., taranakite) do indeed record the paleo-chemistry of the sediment close to the time of its deposition. Therefore, the study of authigenic minerals is applicable to all archaeological, as well as historical, sites. It is especially useful in recognizing areas in sites where wood ash and bones have been dissolved (e.g., [32]). It is worth noting here that based on empirical data of Goldberg and Nathan [8] and Quattropani et al. [22], when a bone-containing horizon is undergoing dissolution due to lowering of pH, aluminum leached out from clays may be incorporated
into the dissolving bone mineral and re-precipitate as the mineral crandallite (CaAl$_2$(OH)$_6$[PO$_4$]$_3$(OH)$_2$). The mineral montgomeryite (Ca$_6$Mg$_2$Al$_4$[PO$_4$]$_3$(OH)$_4$·12H$_2$O) was found in association with crandallite that formed due to bone dissolution [8,14,22]. Therefore, the presence of these two minerals in archaeological sediments is an indication that these sediments were once rich in bones.

Authigenic minerals can be used as indicators for human non-occupation (or abandonment) periods of cave sites. Based on our data (Table 1), the acid insoluble fraction remaining in bat and pigeon guano after degradation comprises only ca. 1–2% by weight of the original material. This is in accord with Hutchinson [10]. It is composed mainly of clay and quartz. Current measurements of guano accumulation in Kebara Cave indicate a rate of guano accumulation that varies between 0 and 10 cm per year. A long period of abandonment of the cave will thus result in a variable pattern of guano accumulation that may reach a meter or more at certain locales (probably under domes). Degradation of a meter of bat guano will result in a 1–2 cm thick deposit of clay and quartz. Considering bioturbation and trampling, the chances of identifying non-occupation, or abandonment horizons, composed purely of clay and quartz, in caves are low. A better indicator for abandonment is thus the occurrence of authigenic minerals and altered clay minerals that form from the degradation of phosphate-rich guano that accumulates when the cave is not occupied.

The fact that guano accumulating on the sediment surface is one of the main driving forces for chemical diagenesis, implies that the overall pattern of diagenesis in a cave is directly influenced by the locations of the bat and bird colonies on the cave ceiling and walls. The other main driving force is the hydrological regime. Thus the diagenetic pattern in the sediments is also influenced by the specific manner in which water penetrates into the cave. As the ceiling domes are the sites where most bedrock dissolution has taken place, they also often reflect the areas of increased hydrological activity. Our observations in Kebara Cave show that fruit bats prefer to roost in domed portions of the cave ceiling, under which the largest piles of guano accumulate. Thus it can be expected that chemical diagenesis will be much more severe under the domes in karstic caves. In our studies of prehistoric caves such as Kebara, Hayonim and Theopetra, we have noticed that chemical diagenesis is less intense towards the cave entrance and around cave walls, and at sites such as Qafzeh there is a sharp contrast between the mild chemical diagenesis on the cave terrace as compared to the intense diagenesis in the cave (S.W. unpublished). We also noticed that in Kebara Cave one of the two locations where ash is still preserved as calcite, is in a location close to the cave wall where the cave ceiling has a convex shape (and hence not preferred by bats for roosting) and it is relatively dry. These rule of thumb correlations may be helpful for excavators needing to choose areas for excavation in a karstic cave.

Authigenic minerals can also be used as indicators of the kind of organic matter that degraded. As taranakite and variscite are formed at low pH conditions they are most likely to form as a result of the breakdown of insectivorous bat guano. Indeed, in many prehistoric caves studied in Israel to date, taranakite is present in Middle Paleolithic layers, a period of time where only insectivorous bats inhabited the area based on paleontological evidence [29]. This implies that generally the degradation of organic matter rich in protein, such as insectivorous bat guano, will result in chemical conditions that will induce the formation of a mineral assemblage similar to the one observed in insectivorous bat guano, as it is richer in phosphate [18] and has acidic pH to begin with. On the other hand, it implies that the degradation of organic matter of a vegetal source will induce the formation of a mineral assemblage similar to the one found in fruit bat guano, as this material is poorer in phosphate and has alkaline pH to begin with. This has implications for open-air sites.

Using authigenic phosphate minerals, we should be able to identify certain activity areas in open-air sites. The presence of authigenic phosphate minerals at a given location is a strong indication of a prior accumulation of phosphate rich organic material, or possibly a mixture of bones and organic matter that was not particularly rich in phosphate. A survey of the phosphate contents in various materials reveals that bones contain the highest amounts of phosphate, followed by feces and urine, protein (i.e., meat, fish, poultry, eggs, milk and dairy products), cereals and nuts, legumes, and lastly fruit and vegetables [6,15,18,27,36]. It is therefore expected that if protein-containing human fecal material was deposited (e.g., latrines, sewers), authigenic phosphate minerals of the low pH–high phosphate suite may be formed (e.g., taranakite, variscite). If the sewage is mixed with lime, then the pH will be higher and dahllite may form. In animal enclosures, animal dung that is composed mainly of vegetal remains should induce the formation of the high pH–low phosphate suite of minerals (e.g., dahllite). Indeed, dahllite was recorded in animal enclosures in abandoned pastoral sites in Kenya [25]. Another area where authigenic phosphate minerals are expected to be found are trash pits/hips. Here, the mineral assemblage will depend on the kind of material disposed off. If this is a mixture of organic matter and bones, montgomeryite and/or crandallite may form. In a trash pit studied in Kenya, composed mainly of wood ash, vegetal matter and some bones, authigenic dahllite nodules were identified [26]. The formation of authigenic dahllite in both trash pits and animal enclosures [25,26] necessitates obtaining additional information on the archaeological context. An analysis of the phytoliths could potentially
shed light on the nature of plant material incorporated in such features. Food processing and storage areas are generally not expected to induce the formation of authigenic phosphate minerals as these areas were probably kept clean.

Finally we should note that the local hydrological regime is also a decisive factor in open-air sites. In a medieval mound in Belgium, Gebhardt and Langohr [7] identified vivianite, a ferroan phosphate mineral, in organic-rich occupational layers. These layers were subject to a local rise in the groundwater table that induced the degradation of organic matter under intense anaerobic conditions.

6. Concluding comment

Understanding diagenesis, although not archaeology per se, is a key to at least partially reconstructing the major losses and additions that take place in the archaeological record over time. This study highlights the importance of degrading organic matter in the diagenetic process, and shows that the authigenic minerals are a valuable, albeit indirect source of information, on the archaeological record. Furthermore, as these changes can take place very rapidly, the use of authigenic minerals to reconstruct aspects of the organic-rich archaeological record can be applied to almost every archaeological site irrespective of age.

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