Sedimentary processes involved in mud brick degradation in temperate environments: a micromorphological approach in an ethnoarchaeological context in northern Greece

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Abstract

Sun dried mud bricks are a common building material across the globe, found in many archaeological sites in the Old World since ca. 11,000 years ago. This material is known to disintegrate due to exposure to the elements, mostly affected by rain. Yet, the geomorphic and sedimentological characteristics of this disintegration process have never been studied in detail until recently. Here we report on mud brick degradation processes observed in an abandoned mud brick village in northern Greece. We demonstrate that mud bricks have unique micromorphological characteristics that differentiate them from natural soils. Upon degradation some of these characteristics are lost (e.g., planar voids after fibrous vegetal temper). Rain initiates brick degradation at the upper parts of walls where from brick material is washed down walls and deposited at their feet, forming a conical talus. The talus deposits show micromorphological features indicative of a variety of flows, including wet and dry grain flows, debris, hyper-concentrated and water flows. These flows seem to operate simultaneously across small distances. These talus deposits are different micromorphologically from natural soils thus their characteristics can be used to identify degraded mud brick material in archaeological sites. This, in turn, may help identify the location of long degraded mud brick walls (in the absence of stone foundations) and identify the relationship between house floors and degraded infill that accumulated on floors following wall degradation. A comparison between the current observations with a previous study we conducted in an abandoned mud brick house in arid southern Israel, illustrates the generality of these low energy slope processes in mud brick degradation, which emphasizes the worldwide applicability of the processes identified in this study.

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1. Introduction

Building with mud, a worldwide construction technique, prevails from the early Neolithic until modern times. The current study is situated within the broad geographical area where building with mud in the past resulted in the formation of mound sites (also known as tells), found from the Balkans in the northwest to India in the southeast (Rosen, 1986). Within this wide geographical area, human use of (mud constructed) space has been extensively studied (e.g., Parker and Foster, 2012; Rainville, 2005). However, degradation of such mud structures, where ancient activities took place, is not well studied. We contend that understanding archaeological domestic mud constructed contexts must take into account both human use of space and how it is affected by mud wall degradation. The importance of studying mud wall degradation lies in it being a source of archaeological infill sediments. Identifying and distinguishing between various archaeological infill sediments which include earth building materials such as mud bricks, beaten earth floors and mud plastered roofs, is not an easy or straightforward task. During excavation, the identification of mud brick material is mostly based on brick shape, if preserved, and the presence of straw or elongated voids indicative of straw temper that was added during mud brick production (Goldberg, 1979; Rosen, 1986). In most archaeological contexts mud bricks do not preserve in their original shape (unless fired, see Homsher, 2012) and may lose their
indicative elongated voids due to degradation processes (Friesem et al., 2011).

The few studies which addressed the issue of mud brick degradation focused on ethnoarchaeological abandoned contexts where a range of degradation stages, from full preservation to complete decay, can be more easily observed (Friesem et al., 2011; Goodman-Elgar, 2008; Koulidou, 1998; McIntosh, 1974, 1977). In his work in Ghana, McIntosh (1974, 1977) did not apply any microscopic analysis and based his insights on excavation and field observations within a modern village and an archaeological site. Koulidou (1998) investigated depositional patterns of mud wall degradation in two abandoned pre-modern mud structures in Northern Greece. She identified a reduction in grain sizes from the wall towards the center of the studied rooms. Goodman-Elgar (2008) studied degradation processes in abandoned earthen dwellings in Bolivia through micromorphological analysis. She highlighted the difficulty to identify degraded mud bricks due to post-depositional processes such as bioturbation (Goodman-Elgar, 2008). Overall, these pioneering studies did not supply unequivocal criteria for identification of archaeological infill sediments that originate from degraded mud bricks.

More recently, some of us studied the degradation processes of mud brick walls in a pre-modern abandoned mud brick house in an arid environment in southern Israel by employing several geoarchaeological methods (Fourier-transform infrared spectroscopy, X-ray fluorescence and micromorphology; Friesem et al., 2011). Due to the nature of the study area, which is surrounded by shifting sand dunes, we were able to identify three types of infill sediments that accumulated within the abandoned house: wind-blown sand, mud slurries from degrading mud brick walls, and mixtures between wind-blown sand and mud slurries. Micromorphology allowed us to pinpoint mud flow as the general mechanism that operates in degradation of mud bricks and infilling of abandoned mud brick houses. In addition, we noted that vegetal temper or its typical pseudomorphic voids (c.f., Goldberg, 1979) are absent in degraded mud brick material. The color, texture and mineralogical differences between the wind-blown sands and mud slurries were so clear (in the specific context studied; see for example Fig. 4 in Friesem et al., 2011) that identifying mud brick material in similar environments is relatively easy. This is clearly not the situation in most other areas of the world, where wind-blown sand or dust are not so voluminous, and it is still highly difficult to differentiate degraded mud brick material from local soils, as pointed out by Goodman-Elgar (2008). We therefore carried out another geoethnoarchaeological study in a region of temperate climate where the amount of wind-blown dust is negligible and amount of rain is higher than in southern Israel. This allowed us to test the generality of the processes identified in the arid environment, and to refine the understanding about the mechanism of formation of degraded mud brick (infill) sediments.

Here we present a study focusing on mud brick degradation processes in two pre-modern abandoned mud structures in northern Greece. The main objective of this study is to identify and describe the geomorphological and sedimentary processes involved in mud structure degradation in order to supply criteria for identification of degraded mud brick sediments. The ultimate goal of this study is to distinguish archaeological infill sediments resulting from mud wall decay, from earthen floors, and from regional soils.

2. The study area

The study took place in the village of Kranionas, located 12 km northwest of Kastoria, at 817 m above sea level (Fig. 1a). Average annual precipitation is around 700 mm spreading relatively evenly along the year, with ca. 50–80 mm per month during fall, winter and spring, and ca. 25–40 mm per month during the summer. The mean annual temperature is 12 °C but may be as low as −22 °C during the winter, with 30–100 days of snow and 80 days of frost per year.
The village of Kranionas was founded at about 1800 AD and abandoned in 1974. Historical and ethnoarchaeological information was recorded during one week of field work in the village in May 2010, based on interviews with two elders (Mr. and Mrs. Lovatis) who were born in the village, lived in it until its abandonment and now live in a nearby village. Almost all structures in the village were built from mud bricks. Certain structures were and still are used after abandonment.

The current study is based on excavation and sampling of two abandoned mud structures previously used as barns by the family of Mr. and Mrs. Lovatis. The study was carried out with their agreement and under their supervision. The first barn measures 5 × 3 m. During the field study, two walls were completely degraded, one wall preserved to a height of ca. 5 m and another wall, referred to in this study as Wall 1, was preserved to a height of ca. 1 m above surface (Fig. 1b). The barn was built before 1930. The roof was made from oak beams and branches covered by commercial roof tiles and the floor was beaten earth. The barn was not in use between 1947 and 1951 when the village was abandoned, then used sporadically for storage of animal fodder until its roof collapsed ca. 50 years later (around the year 2000).

The second barn studied measures 4 × 11 m and its walls are degraded to various stages (i.e., standing to various heights). Within this barn, Wall 2 (studied here) is preserved to a height of ca. 3 m (Fig. 1c). The walls and roof were built following similar methods as in the first barn. The floor was beaten earth. The barn was built (with an adjacent animal enclosure) before 1930 and used for storage of animal fodder until it accidentally burnt down and collapsed in 1980 due to fire that spread from nearby fields into the village.

3. Materials and methods

The two mud structures were trenched. Field observations were followed by sediment sampling and analyses. Mud bricks as well as infill sediments were sampled.

3.1. Field work strategy

One trench was opened cutting through Wall 1 starting ca. one meter outside the structure and ending at the center of the barn's interior (Fig. 2a). The trench was 2.5 m long and 1.3 m deep, reaching ca. 10 cm below the floor level, which was estimated based on the presence of roof tiles and changes in the sediment color and texture, and later corroborated using various geoarchaeological methods (Friesem et al. 2013). Another trench was opened in the second barn from its center to ca. 10 cm from the internal face of Wall 2, thus leaving a section of sediments just adjacent to the wall face (Fig. 2b). The trench was 1.5 m long and ranged in depth between 15 cm in the center of the barn to 80 cm near Wall 2. In both sampling areas, macroscopic remains were recorded stratigraphically, and profiles were drawn and photographed. Bulk (ca. 10 g each) and block samples from un-degraded mud bricks were collected from walls 1 and 2. Infill sediments were sampled in bulk and block formats from beneath the floor vertically to the topsoil.

In order to source the raw material for mud brick preparation, two localities were sampled. The first was soil from a cultivated field on the village's outskirts, a locality indicated to us by Mr. Lovatis. The cultivated soil was sampled adjacent to an electricity pole in order to avoid, as much as possible, disturbance and contamination due to the agricultural activities in the field. This sample was taken ca. 5 cm below surface (i.e., A horizon). The second locality was a ca. 5 m long soil profile, at a road cut 2–3 km west of the village. The soils were sampled in bulk and block formats.

All bulk samples (intact bricks, infill sediments, local soils) were analyzed using Fourier Transform Infrared (FTIR) spectroscopy and all block samples (including the same sediment types as above) were studied micromorphologically.

3.2. Fourier Transform Infrared (FTIR) spectroscopy

This method allows identification of organic and mineral components in bulk samples. Procedures follow the conventional KBr method and interpretation is based on an internal library (at the Kimmel Center for Archaeological Science) of infrared spectra of geological and archaeological materials (Weiner, 2010).

3.3. Micromorphology

Blocks were collected in both barns including intact bricks, the floor level and the infill sediments that accumulated above it.

Fig. 2. The excavated trenches. (a) Wall 1: The trench exposes the exterior fill sediments, the wall's mud bricks and stone foundation, and the interior infill sediments. Box 1 indicates the location of a block that sampled both an in situ degraded mud brick (at its top) and preserved mud bricks below it. Box 2 shows the location of a block where sediments from the barn's interior infill were sampled. Note the sloping sediments on both sides of the wall, forming internal and external taluses. Scale bar is 20 cm. (b) Wall 2: The trench profile includes the beaten earth floor, the roof collapse and the infill sediments that accumulated next to the wall's internal face. Box 1 shows the location where a burnt mud brick was sampled and box 2 shows the location where infill sediments were sampled. Scale bar is 20 cm.
(Fig. 2a and b). Impregnation followed conventional procedures. Thin sections were studied using polarized light microscopes at various magnifications, and micromorphological descriptions follow the terminology of Bullock et al. (1985) and Stoops (2003).

4. Results

4.1. The local soil

Regional soils were sampled and analyzed in order to compare between these soils, mud bricks and beaten earth floors. A complete soil profile was sampled at a road section (Fig. 3a). Soils in the study area develop on polymictic fluvial gravels and belong to the Alfsol group. They are covered by oak forest and grasses. The A horizon is dark reddish brown loam (Munsell dry: 5YR 3/2), less than 50 cm thick. The B horizon is reddish brown loam including gravel (Munsell dry: 5YR 4/4), ca. 1–2 m thick. The C horizon is light brown (Munsell dry: 7.5YR 6/3) composed of clast supported loam. In the village, A horizon soil material sampled from a cultivated field is yellowish red (Munsell dry: 5YR 4/6) while B horizon material exposed in the sampling trenches is reddish brown and includes gravel (Munsell dry: 5YR 4/4).

The mineralogical composition of the loam part of the soil in all horizons, based on FTIR spectroscopy, is dominated by kaolinite and quartz. The B horizon is enriched in clay relative to quartz, as expected. On the mesoscopic scale, the A horizon is homogenous light brown and the B horizon reddish-brown, both having an open porous structure (Fig. 3b, c). In thin section, the A horizon is granular and porous, includes moderately sorted silt to coarse sub-rounded sand (25% abundance). The mineralogy of this coarse fraction is dominated by quartz but also includes grains of feldspar, amphibole, mica, olivine and iron oxide nodules. The groundmass is composed of clay with brownish speckled b-fabric (following Stoops, 2003, photo 7.11). The coarse/fine (hereafter c/f) related distribution is double-spaced porphyric. The microstructure is complex (i.e., a variety of void types, including complex packing voids, vesicles, channels, chambers and vughs with 20–30% abundance). The complex packing voids and channels indicate intensive bioturbation (Fig. 3d). Dusty clay hypocoatings of vughs and horizontal silt cappings indicate dynamic soil and water activity possibly related to the cultivation activities (Pagaliai and Stoops, 2010).

The B horizon appears granular and porous in thin section. The mineralogical composition of the coarse fraction is similar to that of the A horizon, except for the sand-sized particles being sub-angular rather than sub-rounded. The fine fraction is composed of clay with brownish speckled b-fabric and abundant reddish-brown clay coatings (i.e., internal and external hypocoatings and crest-shaped coatings) as commonly found in B horizons (Fig. 3e) (Kühn et al., 2010). The c/f related distribution is double-spaced porphyric. Pedofeatures include iron oxide nodules and manganese oxide hypocoatings of voids. The microstructure is complex, including vughs, chambers and channels with ca. 20% abundance. The microstructure of the B horizon is more compact than the microstructure of the A horizon, likely due to lesser bioturbation.

4.2. Intact mud bricks

The production of mud bricks in Kraniouas was a common practice. Mud bricks were used for building houses consisting of 1–3 stories that served for human residence, animal keeping and storage. According to Mr. Lovatsis the village’s builders used “pure red soil” as the bricks’ raw material, mostly from the upper part of the local soils. Water and the husks left after threshing activities (and occasionally also straw) were added to the soil material and mixed thoroughly. The wet mud brick material was poured into...
moulds measuring 30 × 15 × 10 cm and the bricks were left to dry in the sun. In most cases walls were constructed by first digging a ca. 50 cm deep trench, in which 2–4 courses of field stones were constructed as wall foundation up to ca. 20 cm above soil surface. Rows of mud bricks were then laid on top of the stone foundation using “red soil” mortar as a binder between the bricks. According to Mr. Lovatsis, no special materials were added to the mortar.

Three intact bricks were collected from the preserved parts of the two walls studied. Brick colors in the abandoned village range from pink (Munsell dry: 5YR 8/4) to white — pale yellow (Munsell dry: 5Y 8/1–8/4). The colors of two bricks from Wall 1 (unburnt context) are within this range. FTIR analysis of these bricks indicates a mineralogical composition dominated by kaolinite and quartz, with no significant differences between bricks of various colors, and all compositions are similar to that of the local soil (both A and B horizons). The brick sampled from Wall 2 (burnt context, Fig. 5e) has a gradient of colors including an outer pinkish part (ca. 2–3 mm thick; Munsell dry: 2.5YR 8/4), a middle yellow (ca. 1 cm thick) and black part (ca. 2–3 cm thick; Munsell dry: 10YR 2/1) and a reddish brown core (Munsell dry: 5YR 4/3). The kaolinite infrared spectrum of this burnt brick shows alteration induced by exposure to ca. 450 °C, only on the outermost pinkish 2–3 mm.

One thin section was prepared from each brick. On the mesoscopic scale, the groundmass of the bricks is less porous and the coarse fraction is more homogenously distributed in the matrix compared to local soils (compare Fig. 4a with b). On the microscopic scale, the coarse fraction in a pale orange brick from Wall 1 (Fig. 1b box 1) includes moderately sorted silt to coarse subangular sand grains (25% abundance) composed of quartz, feldspar, amphibole, mica, olivine and iron oxide nodules. This composition is remarkably similar to that in the local soils. A few gravel-sized rock fragments were observed, as well as organic elongated cellulose fragments (grass temper). The grass fragments are randomly oriented within the groundmass (Fig. 5a). Some of them appear broken or sheared (Fig. 5b). The fine fraction is composed mainly of clay with a brownish speckled b-fabric and includes micro-charcoal grains (silt-fine sand size) (<5% abundance). The c/f related distribution is double-spaced porphyric, with more homogeneous spacing relative to that found in the local soils. Voids include vughs, chambers and channels like local soils. They however also include vesicles and planes, the latter are pseudomorph after husk and straw fragments (Fig. 5a). The voids comprise 5—10% of the brick area (in thin section) compared to the 20–30% they comprise in the natural B horizon. The microstructure is thus complex with an overall compacted appearance.

The groundmass includes two fabric types — one dominated by loam and the other dominated by silt. Certain silt fabric domains include features indicative of directional flow and clasts in certain loamy fabric domains show indications for rotation (Fig. 5c). Reddish-brown clay hypocoatings and crescents, in voids and around aggregates are found within the loamy fabric. Rounded, silt-sized grains of clay infillings are also found within the silt fabric domains (Fig. 5d). Both these observations indicate that the soil used for this brick’s preparation originated from a B horizon.

A yellowish-gray brick from Wall 1 (Fig. 1b box 2) has the same micromorphological characteristics as the pale orange brick described above. The burnt brick from Wall 2 (Fig. 2b box 1) has the same mineralogy, structure and pedofeatures as the bricks from Wall 1, but the clay groundmass is darker in color (Fig. 5e), probably due to burning of soil organic matter (Mallol et al., 2013). Charred vegetal remains are indeed abundant (5%) (Fig. 5f).

These observations support the reports of our informants that the bricks studied here were prepared from the local red (B horizon) soil. The presence of elongated organic cellulose fragments as well as randomly-oriented planar voids reflects the intentional addition of straw and chaff during brick preparation. Evidence for pugging (i.e., mixing/kneading of the soil material, temper and water during brick preparation) includes the bricks’ compact structure, decreased porosity, relatively homogenous distribution of the coarse fraction within the groundmass, and the presence of pressure-induced deformation pedofeatures (i.e., shearing, rotation, and directionality of flow). These observations are crucial for identifying mud bricks as a worked/prepared construction material that differentiates them from unworked natural soils.

4.3. Mud bricks in the process of degradation

4.3.1. Field observations of degrading walls

Many walls in the village show different states of preservation and/or degradation. Friesem et al. (2013) have shown that mud wall
preservation depends primarily on the presence of an intact roof. When roofs degrade and collapse, mud walls start degrading in three major ways: gravitational fall of single bricks and formation of single brick piles at the feet of walls (Fig. 6a), collapse of intact wall segments associated with wall cracking/fissuring (Fig. 6b and c), and gravitational slurry movement of brick material along walls (Fig. 7a and b). Such slurry movements are pronounced at the upper, exposed, parts of un-protected walls resulting in the loss of the original size and shape of the topmost brick courses, formation of sharp edges at the top part of such walls, and at the same time accumulation of washed-down brick material at the foot of degrading walls (Fig. 7c, d and e). Bioturbation in the form of plant overgrowth may occur on wall stumps (Fig. 7d). The combination of the above mentioned collapse, bioturbation, and mud slurry movements lead to the formation of a mound in proximity to the degrading walls (Figs. 6d and 7e). Below we present the sedimentological characteristics of these mud mounds.

4.3.2. Wall 1: macroscopic observations and microscopic analyses

Wall 1 consists of 4–6 courses of bricks above its stone foundation, reaching a maximum of 50 cm above the current surface. Its general appearance resembles a small mound (Fig. 2a). A talus of mud brick material is found on both sides of this degraded wall. The lowermost sediment exposed by trenching is reddish brown horizontal soil (Munsell dry: 5YR 4/4) overlain by horizontally oriented roof tiles. The horizontal surface reflects the beaten earth floor of the barn which is overlain by the barn’s collapsed roof. Above the roof tiles, an inclined massive sediment pile stretches ca. 80 cm away from the wall. This sediment pile includes a light brown bottom part (Munsell dry: 7.5YR 6/3) and a brown layer on top (Munsell dry: 7.5YR 4/2), ca. 20 cm thick, interpreted as the topsoil. The bricks buried under the topsoil (reddish-brown, Munsell dry: 5YR 4/3 at the top and pale yellow, Munsell dry: 5Y 8/2 at the bottom) still have sharp rectangular edges and dark red mortar is preserved between them (Fig. 2a).
FTIR analysis of all sediment types exposed in the profile described above have the same mineralogical composition, i.e., kaolinite and quartz. Micromorphology enabled to identify stages of degradation associated with the bricks of Wall 1. The lower 3–4 brick courses (above the stone foundation) appear well preserved on the macroscopic scale, i.e., their rectangular shape is clear. Their micromorphology is similar to that described in section 4.2 above. The sediment from the uppermost 20–30 cm of Wall 1 represents ca. 1–2 courses of in situ degraded brick/s (Fig. 2a box 1). Here, the brick macroscopic shape is not clear to the naked eye. On the mesoscopic scale, the topmost part of these degraded bricks appears banded (Fig. 4c). The reddish bands are loam dominated and the yellowish bands are silt dominated. Reddish clasts float within...
The main differences between the in situ degrading bricks and intact mud bricks are the presence of clasts surrounded by a continuous clay coating (Fig. 9b) termed “rolling pedofeatures” by Boschian (1997) and Angelucci and Zilhão (2009). A lenticular microstructure formed by lensoid aggregates associated with a silty groundmass has been observed, possibly indicating freezing and thawing (following the definitions of Van Vliet-Lanoë et al., 1984) (Fig. 9c). Similar to the in situ degrading bricks, the infill sediments lack elongated vegetal matter and/or planar pseudomorphic voids after brick vegetation. The clay hypocoatings and crescents ‘inherited’ from the local soil B horizon are not found within a continuous soil matrix, rather, they are found only within mud brick aggregates that are dispersed in the infill matrix (<5%).

The contact between the barn’s beaten earth floor and the overlaying infill sediment is diffuse and cannot be discerned even microscopically (see Friesem et al. 2013 for the use of phytolith and phosphate concentrations for identification of floor surfaces when micromorphologically such a contact is diffuse).

4.3.3. Wall 2: macroscopic observations and microscopic analyses

At the time of field work, Wall 2 stood to a height of ca. 3 m. The profile of the sediments at its foot included the beaten earth floor at the bottom, overlain by black and gray sediments covered by roof tiles (Fig. 2b). The black, gray and roof tile layers are horizontal (Fig. 10a). They formed when the barn burnt down in 1980. Brown sediments from the degrading wall accumulated above the roof tiles, forming a talus inclined towards the barn’s center. The lower part of the talus is light brown (Munsell dry: 7.5YR 6/3) and ca. 20 cm thick (close to the wall). The upper part of the talus is brown (Munsell dry: 7.5YR 4/3), ca. 10 cm thick, interpreted as topsoil. Thin coarse-grained lenses are interbedded in a fine clayey matrix (Fig. 10a).

Bulk samples from the beaten earth floor, bricks along the wall and the two types of infill sediments described above showed no significant difference in their mineralogical composition based on FTIR analysis, dominated by kaolinite and quartz.

The lower reddish brown soil is a disturbed B horizon. The black and gray layers are composed of activity remains and roof collapse (Friesem et al. 2013). The light brown infill sediment above the collapsed roof tiles (Fig. 2b box 2) possesses the same coarse and fine components and abundance as intact bricks, which are also similar to the light brown talus sediment near Wall 1. Void types include vughs and vesicles and the microstructure is massive but rather open. Elongated vegetal fragments or their pseudomorphic voids, which are typical of intact bricks, are absent. Crude linear arrangements of sub-rounded clasts are associated with a sorted silty groundmass (Fig. 10b and c). Overall, the light brown infill sediment next to Wall 2 has microstructure and pedofeatures similar to those identified in the talus infill sediments sampled near Wall 1.
5. Discussion

The study presented here primarily deals with geomorphic processes that occur next to degrading mud brick walls. While supporting the preliminary findings of Friesem et al. (2011), the current study adds new insights into the process of mud brick degradation and provides new means for differentiation between natural soil, worked soil/mud bricks, degrading worked soil/mud bricks, and infill sediments derived from degraded mud brick walls—all having the same chemical and mineralogical composition.

Field observations in the current study (but also in previous studies, e.g., Koulidou, 1998) show that mud structures degrade into small mounds apparent by the formation of a talus (slope) on both sides of degrading walls. Thus depositional processes next to mud brick walls can be regarded as slope processes resulting in slope deposits. Rainsplash causes initial disaggregation and sealing of mud brick surfaces, similar to its effect on soil surfaces (Morgan, 2005), initiating a variety of flows which are classified according to the water content involved in sediment translocation, the size of translocated clasts, and water energy (velocity) (Jakob and Hungr, 2005). Processes along slopes are related to a variety of flows that may operate simultaneously. Apart from wet flows, slope processes also involve dry gravitational movements (colluviation).

5.1. Slope processes involved in mud brick degradation

Three main wet flow types are related to slope processes. Water flow is characterized by relatively small quantities of sediment (generally less than 4 vol% or 10 wt%; i.e., Wannanen et al., 1970)). The sediment is usually fine-grained and has little effect on flow behavior. Hyperconcentrated flow is classified by more suspended sediment concentration (between 20 and 60 vol% or 40–80 wt % (Beverage and Culbertson, 1964; Pierson, 2005)) and the sediment is usually fine- and coarse-grained. Debris flow is attributed to flows which transport more sediment than water. Sediment concentrations are often in excess of 60vol% or 80wt% and more than 50% of the particles are larger than sand. In contrast to water flow, the suspended sediment in debris flow plays an integral role in the flow behavior and mechanics (Costa, 1984). When sediment is supported by grain-to-grain interactions, either as a dry flow or as a wet flow (where the fluid acts only as a lubricant), the flow is regarded as grain flow (Postma, 1986). Overland flows, which are very shallow wet flows, often have lateral differences (on the scale of centimeters) depending on the ratio between water and sediment (Bertran and Texier, 1999). Thus, an overland flow may be composed of areas that are best defined as hyperconcentrated, debris and/or water flow, all occurring simultaneously.

Flows are not categorized only by the relative sediment concentration within the flow, but also based on features such as discharge, depth, velocity, particle size and distribution, sediment deposition and more (Jakob and Hungr, 2005). Most studies of flow deposits focused on macroscopic features. Bertran and Texier (1999) worked on microfacies and microstructures of slope deposits and supplied micromorphological criteria for flow deposits at a microscopic scale. They mention that sedimentation along slopes is discontinuous and that numerous processes such as biologic and anthropogenic activity, freezing and thawing, run-off and surficial creep can modify the deposits to varying degrees between successive sedimentary events (Bertran and Texier, 1999), Menzies and Zaniewski (2003) conducted a micromorphological study of debris flow sediments. They reported large turbate structures, presumably indicative of intense deformation of plastic/ductile material. They also observed recurrent bands of clay that presumably developed following flow deceleration and dewatering.

The study presented here, at the abandoned village of Kranionas, identifies various gravitational and flow processes associated with mud brick wall degradation. On the macroscopic scale, we observed gravitational collapse of intact wall segments (Fig. 6c) following cracking and fissuring (Fig. 6b), rolling of single bricks (Fig. 6a), mud slurry movement along standing walls (Fig. 7a and b), and formation of talus slopes on both sides of degrading walls (Figs. 6d and 7e). The underlying mechanism that produces the talus is the initial movement of mud along standing walls in the form of mud slurries. These movements have apparently been initiated by rainsplash and involved enough water to form the conditions (e.g., brick disaggregation, water velocity) needed to detach soil material from intact bricks. Depending on the amount of water (discharge) involved in the formation of these mud slurries, different flows will be produced. Small amounts of water are expected to produce debris flows and higher amounts of water are expected to produce hyperconcentrated flows in a form similar to sheet wash (thin water films). We have not observed these flows directly, however, macroscopic and micromorphological observations of the talus sediments suggest their presence.

Macroscopically, the moderate sorting and the weak bedding of clasts with the inclination along the talus slope (Fig. 2a) suggests colluvial—wet and/or dry—grain flow (i.e., Karkanas et al., 2012). On the microscopic scale, the presence of continuous clay coatings around clasts that are embedded in the sediment matrix (Fig. 9b) — also known as “rolling pedofeatures” (Angelucci and Zilhão, 2009; Boschian, 1997) — indicate debris flow. The absence of packing voids supports this interpretation, i.e., a wet rather than dry grain flow (Bertran and Texier, 1999; Pierson, 2005; Postma, 1986). Further support to the presence of debris flows is the porphyric related distribution (i.e., coarse grains floating within a fine matrix) associated with vughs and vesicles, as well as the presence of red brick fragments embedded within the brown talus matrix. Flow direction is implied from weak sorting and layering of coarse grains.
Lower energy water flows (hyperconcentrated sheet wash) may also have acted on sediments in Kranionas, possibly in the upper parts of in situ degrading bricks as well as in infill sediments. This is evident by the presence of silty groundmass, sometimes inter-bedded with clay-supported silt. These observations may indicate localized translocation of clay leaving a concentrated silty fraction. These features are expected in hyperconcentrated flows that due to their lower energy tend to form minimal sorting of clasts. Evidence for differences in flow regimes and energies is indicated by the presence of discontinuous sedimentary structures (see Fig. 10b and c) (Bertran and Texier, 1999; Pierson, 2005). Some of the laminae that show better sorting are probably transient phases to water flow. We note that while flow direction was somewhat apparent micromorphologically, it was not always clearly observed macroscopically in field profiles. In the dry environment of Gvulot, however, flow direction was apparent both macroscopically and micromorphically (Friesem et al., 2011). In the absence of clear macroscopic bedding next to wall stumps in archaeological contexts, only micromorphological criteria will enable determining whether or not infill sediments derive from degraded mud brick walls.

Except for rain, Kranionas accumulates much snow during the winter and frosts may occur in harsh winters. Micromorphological pedofeatures characteristic of incipient frost activity include localized platy structures with deformation features, and often embedded in a matrix with single grain sand and silt (Bertran and Texier, 1999; Van Vliet-Lanoë et al., 1984). These pedofeatures, although poorly developed, may be present in the infill sediments studied here, indicated by subrounded aggregates and lenticular silty structures (Fig. 9c) (see also Karkanas, 2002 for subrounded spherical clasts formation due to freeze and thawing cycles).

Other post-depositional processes that occur in the degraded mud brick talus sediments as well as on the mud bricks themselves include plant and animal turbation, evident by the presence of chambers and channels.

### 5.2. The life cycle of mud bricks

Ethnographic, ethnoarchaeological and geoarchaeological studies have shown that raw material for mud brick preparation is usually collected from soils in the vicinity of settlements (i.e., Goldberg, 1979; Homsher, 2012; Nodarou et al., 2008; Rosen, 1986). Other studies have shown that material suitable for mud brick preparation should be composed of ca. 25–45% clay, and the rest of material is in other size groups (Canaan, 1932–1933; Goldberg, 1979; Homsher, 2012; McIntosh, 1974; Morgenstein and Redmount, 1998; Nodarou et al., 2008; Rosen, 1986). Ethnographic studies also highlight the addition of vegetal matter to the mineral raw material during the brick manufacturing process. In both study areas we worked at, Gvulot in southern Israel and Kranionas in northern Greece, these parameters are met in intact bricks. The process of kneading (pugging) the wet soil material with the various temper materials was not intensive enough to break and eliminate the clay coatings and in fillings indicative of the B horizon parent material in Kranionas. The pugging process is also evident based on the presence of broken and sheared brittle vegetal fibers, associated with directional flow of silty material. The silty matrix is clearly originating from a soil B horizon because it includes silt-sized grains of broken and rounded clay in fillings. This indicates that during brick preparation clay washed out from certain loamy areas thus leaving silty domains. This process may be regarded as elutriation. We stress that the process is elutriation rather than eluviation, because while eluviation implies only movement of clay downwards, elutriation indicates movement of clay also sideways. In addition, we observed rotational features associated with both the loamy and silty domains, indicating ductile deformation.

The moulding process in brick preparation apparently results in compaction of the mud brick material, as micromorphologically it is denser than the relatively open structured local soils. A prominent feature indicative of intact bricks is the planar voids which are pseudomorphic after the vegetal temper (Goldberg, 1979; Matthews et al., 1997). In Gvulot as well as Kranionas, the vegetal temper preserves in its organic form for decades, as long as the bricks are intact and/or protected by a roof (i.e., kept dry).

Upon abandonment, bricks start to decay once they are not protected from rain by a roof (Friesem et al. 2013). Early stages of degradation occur while the bricks are still emplaced in the wall (i.e., in situ degradation). Coarse and fine materials wetted by rain form overland flows (very shallow film/sheet wash water and hyperconcentrated flows, i.e., mud slurries) in temperate as well as arid environments. The rate of the process differs according to annual amount of precipitation in each area. In advanced stages of in situ brick degradation (exemplified in Wall 1 in Kranionas) the microstructure of an in situ degraded brick is still massive and dense, but the pseudomorphic planar voids after vegetal matter disappear, indicating the degradation of this organic material and collapse of the pseudomorphic voids.

The next stage of degradation involves flows of various types. Below we compare our observations from the current study in the temperate environment of Kranionas with our previous study in the arid environment of Gvulot, southern Israel (Friesem et al., 2011). This comparison shows the generality of the mechanisms underlying mud brick wall degradation because these two geographic–climatic examples form a continuum of geomorphic–sedimentological processes according to amount of rain and amount of wind-blown material. Bricks may be fragmented mechanically into gravel and roll gravitationally down the wall or talus. This was clearly observed in the arid environment of Gvulot, while in the temperate environment of Kranionas such intact brick fragments are less common and less clearly defined. Micro-charcoal fragments observed in intact bricks in Kranionas seem to be present in the infill sediments in much lower quantities, possibly due to partial degradation (dissolved/dissociated by water?) and/or washed further away due to its light weight. All in all, the washed materials are carried away from the wall and are redeposited next to the wall, forming a talus from the wall outwards.

Clasts of the brick coarse fraction undergo gravitational movement along the slope. In the dry environment of Gvulot this was evident by the formation of microscopic laminae of coarse sand indicating dry colluvial grain flow. In the temperate environment of Kranionas this is evident by weak bedding of clasts oriented with the talus inclination (i.e., dry grain flow), the presence of “rolling pedofeatures” (i.e., debris flow) and changes in sorting. In Gvulot, changes in sorting were also observed in the form of clay coatings and graded bedding. This probably reflects local short-term puddling following strong rain events (southern Israel is characterized by short episodes of torrential rain). It is possible that certain sand layers found at the topmost part of finer-grained matrix formed by buoyancy of coarse grains within hyperconcentrated flows in Gvulot (e.g., Fig. 9b in Friesem et al., 2011). Cycles of graded bedding were identified along the stratigraphic sequence in Gvulot, enabling to identify separate flow events. In Kranionas rain is better spread throughout the year thus translocation of grains is gentler and to different depositional distances, whereby during water flow only clay is washed away from the coarse fraction (elutriated) leaving behind patches of silty groundmass. Overall though, the majority of flow in Kranionas is in the form of hyperconcentrated flows, resulting in gentle carriage and deposition of sand, silt and clay. Therefore, in Kranionas it was
not possible to ascertain separate flow events. The overall micro-
structure of degraded brick talus/infill sediments is less massive
and more open than those of intact and in situ degraded bricks,
including crude bedding due to flow processes.

Bioturbation due to activity of plant roots and burrowing ani-
mals is evident by the presence of channels and vesicles in both
Gvulot and Kranionas, whereas in Kranionas weak frost activity
was also possibly present. These post-depositional processes may
damage the bedding attributed to slope deposition. All natural
processes described above do not differ between the burnt and
unburnt areas.

5.3. Identifying degraded mud brick sediments in the archaeological record

Intact whole or fragmented mud bricks can be easily identified
in archaeological sites either by the naked eye and/or micro-
morphologically. The identification of degraded mud brick infill
sediment in archaeological sites is, however, more complicated and
requires several lines of evidence. At a macroscopic scale, the
context of the archaeological infill sediment is important to know,
as infill sediments near walls are immediate suspects for origi-
nating from wall degradation processes (though the identification
and exact location of mud walls is not always an easy task in
archaeological sites, unless there is a stone foundation to the brick
wall). Microscopic criteria should be added in order to reach an
unequivocal identification of degraded mud brick infill sediments
in archaeological sites.

In both Gvulot and Kranionas the talus formation next to
degrading walls results, post-depositionally, in a U-shaped basin
between adjacent opposing walls. In Gvulot, infilling rate is higher
than in Kranionas due to the large amounts of wind blown sand.
With time the area between the walls is flattened (becoming
horizontal) but the U-shaped basin between walls can be observed
in excavation profiles in the form of alternating thin gray (mud
brick derived) and yellow (wind blown) sedimentary layers
(Friesem et al., 2011). Wind blown sediments do not occur in
Kranionas and the abandoned mud structures are infilled by
degraded mud brick material only, forming a U-shaped basin with
no macroscopically resolved bedding. This latter observation
highlights the importance of using micromorphology. When
aiming to identify degraded mud brick infill sediments in an
archaeological context, the combination of field observations at
the macro- and meso-scales of the fabric of the deposits as well as
the microscopic observations of the microfabric are important and
can lead to a safe interpretation. The microscopic criteria that are
most useful include graded bedding alternating with variable
amounts of wind blown sediments, in arid environments, and
indicators for slope processes – such as rolling pedofeatures, weak
bedding and sorting, all of them alternating and quickly changing
relative to each other laterally, or, interfingered – in temperate
environments. Remnants of the original mud brick material have
to be identified in order for the different decay phases of the
material to be established; for example the assignment of the red
aggregates to mud brick in the case of Kranionas is based on the
similarity between the aggregates and intact mud bricks. The
above natural formation processes may be affected by cultural
processes, especially at multi-layered sites where pitting, trench-
ing, leveling and packing may have been practiced by the site’s
inhabitants. While these activities may truncate and disturb
naturally formed sediments at abandoned parts of a settlement,
they are not expected to eliminate them. Thus we expect that
abandoned reworked contexts could still be identified at multi-
layered archaeological sites based on the criteria presented in
this study.

6. Conclusion

Mud brick wall degradation is triggered by gravity and water in
both ends of the Mediterranean climatic region, i.e., arid as well as
temperate environments. Water and gravity act together in forming
a variety of dry and wet flows, resulting in the formation of a talus
on both sides of degrading walls and a U-shaped basin that infills
abandoned structures. These taluses include sedimentary features
characteristic of slope deposits that are best identified micro-
morphologically, especially in non-arid environments where such
taluses appear homogenous to the naked eye. Identification of such
slope deposits in archaeological sites where building with mud
took place may thus enable identifying periods of abandonment,
and differentiate these deposits from beaten earth floors as the
latter still posses natural soil microstructures. In addition, the
ability to identify abandonment periods based on sedimentological
features will highlight such strata in tell sites, where much
emphasis is usually put on destruction layers.

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