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Abstract

Excavations of a kitchen at Escalera al Cielo in the Puuc Maya region of Yucatán, Mexico uncovered a concentration of fired clay balls (ca. 3–5 cm in diameter), in addition to other de facto domestic refuse. The kitchen pertains to an intensively excavated elite residential group that was rapidly abandoned sometime near the end of the Terminal Classic period (A.D. 800–950), resulting in floor assemblages that provide an opportunity to explore the types and distribution of daily household activities. The results of experimental replications and a suite of analyses comprising modal analysis, ceramic petrography, Fourier transform infrared spectroscopy (FTIR), and microbotanical residue analysis reveal aspects of clay preparation, firing temperatures, repeated use of the balls, firing conditions, and specific plant food or fuel residues adhering to them. We show that the fired clay balls were manufactured with local, clay-rich soil and employed by the inhabitants of Escalera al Cielo as heating elements; relatively high concentrations of microbotanical residues from edible plants adhering to them support the hypothesis that they were involved in kitchen activities related to food processing.

Keywords: Fired clay balls; Puuc Maya; FTIR; Ceramic petrography; Microbotanical residues; Culinary equipment

1. Introduction

At the site of Escalera al Cielo (EAC), an elite residential settlement located in the Puuc Maya hills of Yucatán, Mexico, unusual contexts containing de facto refuse have yielded a new category of artifact. In 2009, a deposit of fired clay balls was excavated from the back edge of a kitchen at EAC (Gallareta et al., 2008; Simms et al., in press) (Fig. 1). Fired clay balls have been described from a variety of archaeological contexts worldwide (e.g., Atalay, 2003, 2005; Ford and Webb, 1956; Gibson, 2000), but have never been systematically studied in the Maya area. The most common interpretations of clay ball function include ammunition for weapons (such as slingshots) and culinary equipment. Ancient cook-stone technologies in both the Old and New Worlds, dating back as far as 30,000 B.P., have also been extensively documented (e.g., Thoms, 2008, 2009; Wandsnider, 1997), and guide interpretations of the use and function of fired clay balls from EAC.

The fired clay balls from EAC were concentrated in the upper ca. 30 cm of four contiguous 2 × 2 m excavation units, and total 77 hemispherical to complete balls and 912 smaller fragments (Figs. 2, 3). Each ball is approximately 3–5 cm in diameter, representing a handful of clay. Based on macroscopic observations and a few reports of similar objects from domestic contexts at other sites in the Puuc region—Xkipche (Voss N. and Lizarraga Perez, 2006), Labna (T. Gallareta Negrón, personal communication 2009), and Nucuch Tunich, a satellite of Yaxhom (W. Ringle, personal communication 2011)—we posit that the balls formed part of the culinary toolkit.

The aim of our study, therefore, was to test this hypothesis by studying the material properties of the clay balls. The first step involved recording modal data on the entire assemblage. A sample of six complete balls and local, clay-rich sediments that potentially served as the raw material were then exported; these materials were analyzed by ceramic petrography, Fourier transform infrared spectroscopy (FTIR), and extraction of microbotanical residues (i.e., phytoliths and starch grains). To facilitate interpretations about the use and function of the balls, the design also included experiments with test balls reproduced with fresh local soil and fired in different conditions.

1.2. EAC and the Puuc Maya region

EAC is located in the Puuc Maya region of Yucatán, Mexico, and lies 1.4 km from Kiuic, the closest urban center. The site comprises two major architectural concentrations, one on each cusp of a 60 m-tall cone karst hill, with additional low, mounded platforms and domestic features situated along a 200 m north-south trend (Fig. 2). Approximately 85% of recovered ceramic material and radiocarbon dates from wood charcoal correspond to the Terminal Classic period (A.D. 800–950) and a single construction phase. EAC is an extended or multiresidence household as defined by its constrained hilltop location and the form of its architecture and features, which probably represents a coresidential economic group (Gallareta et al., 2008). A total of eight water cisterns, 28 (limestone) grinding stones, and five quarries for raw lime plaster and stone construction materials are dispersed within and between the northern and southern architectural concentrations.

The fired clay balls were found on the back corner of a kitchen in the northwesternmost residential group, which corresponds with a single household (Fig. 3). Over three field seasons, indoor and outdoor spaces in this group were investigated encompassing a three-room stone-vaulted residence and two associated food storage and/or preparation buildings. All of the investigated buildings at EAC contain evidence of a rapid, planned abandonment of the site sometime during the end of the Terminal Classic period in the form of rich floor assemblages representing de facto refuse (Simms et al., in press). Ongoing analysis of reconstructable ceramic vessels, stone tools, personal adornments, burials, and other materials are revealing specific domestic activities performed at EAC and the patterns of everyday life within investigated households.

EAC is situated in the Bolonchén District of the Puuc region, which is characterized by cone karst hills ranging from 40 to 60 m in height, with intervening flatlands containing deep, clayey soils (Wilson, 1980). Agriculture is dependent upon variable rainfall owing to a lack of perennial water sources. Therefore, the thousands of water cisterns excavated into the limestone bedrock associated with prehispanic residences were essential for water provisioning during the November to April dry season (Barrera Rubio, 1987; McAnany, 1990; Thompson, 1897). Every residential group at EAC contains at least one water cistern. Limestone is the only locally available stone material so the prehispanic Maya imported chert, obsidian, and jadeite cores and finished implements. Vegetation in the Puuc is characterized as a deciduous seasonal forest (Wilson, 1980), almost all of which is secondary regrowth as a result of clearing for agriculture and modern cattle ranching.

Ethnographic and ethnohistorical literature (beginning with 16th-century accounts from Spanish missionaries) from the region provide a rich foundation for exploring possible interpretations about prehispanic Maya lifeways. Of particular relevance to our study of fired clay balls are frequent accounts of pit oven (*pib* in Mayan) cooking. To prepare the *pib*, men first dig a shallow pit, then fill it with firewood and stones. The fire is lit and the wood reduced to embers, at which point packages of food are placed on the hot stones. Leaves and earth are heaped over the food to seal in heat and smoke, and cooking takes at least one to two hours.

Wandsnider (1997) summarizes pit oven cooking times for a variety of foods based on requirements for chemical changes such as toxin oxidation and hydrolysis: e.g., meat dishes can take two to fours hours; husked, roasted sweet corn is cooked in excess of 12 hours; and inulin-rich foods such as roots and agave tend to be cooked in large quantities for a day or more.

On festive occasions in modern Maya communities, men make bread in the *pib* (e.g., Anderson et al., 2005; Coe 1994; O'Connor, 2010); one recipe involves maize dough mixed with ground squash seeds and formed into special shapes. In addition, banana leaves containing squashes, sweet potatoes, manioc, yam, and *jicama* are cooked in the oven, and occasionally meat (Redfield and Villa Rojas 1962 [1934]: 41). A pair of riddles from the *Chilam Balam of Chumayel* (Roys 1933: 96–97)—one of a series of books that record aspects of Yucatec Maya history from the time of the Spanish conquest—make mention of sweet manioc and *macal* [*Xanthosoma nigrum*] baked in a *pib*; the latter should be extinguished with honey while hot from the oven. Coe emphasizes the importance of root crops and squash fruits in the Maya diet, both often prepared (baked) in the *pib* (Coe 1994: 164). She also mentions the use of hot stones dropped into a pot of ground, cooked beans and ground squash seeds to dehydrate the mixture, which could later be reconstituted by adding water (Coe 1994: 163). Cogolludo (1954–1955, 3: 267–268) describes a dish consisting of a whole turkey covered in dough, wrapped in a mat, and cooked in a *pib*, delivered to a 17th-century Spanish missionary expedition by a Maya chief as a symbol of war. Below, we present the results of our analyses of the EAC fired clay balls that support our interpretation of their use in similar cooking or heating installations.

1.3. Archaeological examples of cook-stone and clay ball cooking technology

Thoms defines cook stones—often classified archaeologically as “fire-cracked rock”—as hot rocks that serve as heating elements in earth ovens, steaming pits, surface griddles, and for stone boiling (2009: 573). Cook stones have been documented both ethnographically and archaeologically worldwide (e.g., Driver and Massey, 1957; Fitz-Patrick and Kimbuna, 1983; Sassaman, 1995; Thoms, 2008, 2009; Wandsnider, 1997). They present evidence of having been heated to temperatures exceeding 500°C, a range typical of cooking fires, and are especially useful for their abilities to retain heat, spare fuel, and generate steam or boil water (Thoms, 2009: 577). Beyond their culinary potential, cook stones can also be employed for general heating purposes and in steam baths, among other possible uses.

Perhaps the best-known example of clay ball cooking technology comes from the Late Archaic period (ca. 1650–600 B.C.) site of Poverty Point, Louisiana (Ford and Webb, 1956; Gibson, 2000). The inventory includes several tons of clay balls averaging 4.5–5 cm in diameter and in a range of shapes. The Neolithic village site of Catalhöyük (ca. 7300–5000 B.C.) in Anatolia also contains a large inventory of fired clay balls (Atalay 2003) in similar shapes and sizes (6.3 cm mean diameter). The balls from both of these sites exhibit finger impressions to form grooves, incisions, and roughened surfaces, which served to increase heat diffusion across enlarged surface areas and permitted easier manipulation with sticks or tongs. For the Catalhöyük assemblage, Atalay (2003, 2005) observed heterogeneity in fabric type, uneven heating, and storage and use of broken or cracked balls. Clay balls were recovered from pit ovens, hearths, and other fire installations leading investigators of both sites to conclude that they served as a major cooking technology. In addition, both sites contain abundant clay resources but lack stone with a high capacity for heat retention, as at EAC.

2. Materials

During excavation, the fired clay balls from EAC were identified as a special category of artifact and collected in plastic bags, with one bag per lot. In addition, multiple samples of sediments surrounding the clay balls were collected. The six balls selected for export and microanalyses remained unwashed; each was placed in a separate polyethylene bag in a clean lab environment and transported to Boston University. The rest of the balls were then washed in order to conduct modal analysis at the BRAP laboratory in Oxkutzcab, Yucatán. To investigate the production and the use of the clay balls, control samples of local sediments were collected from two test pits (0.5 × 0.5 m) located around the base of the EAC hill (Fig. 1); the samples comprise material from beneath the humic horizon at 10–20 cm below the surface and from 20 cm to bedrock (approximately 20–30 cm deep).

3. Methods

3.1. Modal data

For the entire assemblage of fired clay balls, modal attributes such as size, weight, shape, core and surface color, fire darkening, inclusions, and structure of the fabric were recorded. In this manner, basic patterns became evident and it was possible to determine how representative the fine-resolution data from the six balls were of the overall assemblage. Both the modal and microscopic data revealed a surprising degree of heterogeneity. Nevertheless, four basic subcategories were defined based on macroscopic observations that can be correlated with the microscopic data (see Section 4.1.).

3.2. Petrographic thin sections

The control sediments, the six archaeological clay balls, and one experimental clay ball were impregnated with unpromoted polyester resin and sent to Spectrum Petrographics Inc. (Washington, USA) for 30 μm-thick thin section preparation. The thin sections were analyzed using a polarizing light microscope (Nikon Labophot-pol), and described following standard micromorphological criteria (Bullock et al., 1985; and Courty et al., 1989; Whitbread, 1989). Sample preparation and analysis were conducted in the Microarchaeology Laboratory at Boston University.

3.3. Experimental work

Preliminary petrographic analysis revealed that the clay ball raw material is consistent with local sediments (control samples). Therefore, experimental replication studies were conducted with the control samples in order to understand the observed differences in color—especially between the core and surface of the balls—and structure. The experiments involved the preparation and firing of clay balls, in addition to loose control soils, at different temperatures and durations to create a reference database for comparison with petrographic and mineralogical studies of the archaeological balls. The experimental balls were prepared using control sediments from the deepest level of test pit 1 (ca. 20–30 cm deep, overlying bedrock). After gently breaking up the sediment with a mortar and pestle, it was passed through a 2 mm sieve to remove coarse rock fragments and pieces of organic material. To the sieved material, just enough deionized water was added to evenly wet the clay-rich sediments and form 12 (roughly spherical) balls approximately 4 cm in diameter. Finally, the balls were allowed to dry for three days in a drying oven at 70°C (see Section 5.).

The experiments were performed in two different firing environments: closed (muffle furnace) and open (outdoor fire pit). For the first set of experiments, dry sediments as well as experimental clay balls were tested, and for the second set only experimental clay balls were tested. Dry sediments were fired to calibrate the thermal behavior of the local soil and firing experimental clay balls allowed us to calibrate the thermal behavior of the local soil in the form of balls. We repeated the experimental clay ball firing twice for one set of parameters (625°C for four hours in the muffle furnace) to verify the reproducibility under controlled conditions. A single test was conducted for each of the remaining 11 experimental balls.

3.3.1. Muffle furnace experiments

The control sediment samples (1 g each) were placed in crucibles and heated at 315°C 400°C, 500°C, 600°C, 700°C, and 800°C. To gain insight on the kinetics of the reactions, for each temperature a set of samples was fired to a flash point (i.e., it was removed as soon as the oven registered the designated temperature) and a second set of samples was fired for two hours at that temperature.

Several furnace experiments were conducted with the experimental clay balls: one at 550°C for two, four, and eight hours; a second experiment was conducted at 625°C to a flash point and for four hours; and a third experiment was conducted at 700°C to a flash point, two, four, and eight hours. All oven experiments utilized a Fisher Sci Isotemp Programmable Muffle Furnace.

3.3.2. Open fire experiments

To explore the effects of open firing conditions, which have been suggested for ceramic production in the region, a second set of experiments was carried out. Three balls were placed in the base of a shallow pit and a fire was built on top of them (using available maple wood and pine brush for kindling). Following similar experiments designed to test Philistine hearth pyrotechnology (Gur-Arieh et al., 2012), temperature was measured directly on top of the clay balls every 15 minutes with a thermocouple (UEi DT304 Digital Thermometer with a K-type probe). Once the wood caught fire, the temperature rose quickly (reaching 565°C at 15 minutes). Wood was added as necessary to keep the fire burning. The three balls were left to cook in the fire pit for two, four, and eight hours, respectively. The temperature ranged from 502°C to a maximum of 714°C; over eight hours the mean temperature was 548°C.

At the end of each set of experiments, the experimental balls were sliced in half and subsampled for further analysis on the external surface and in correspondence with every internal change of color.

3.4. Fourier transform infrared spectroscopy (FTIR) and microspectroscopy (mFTIR)

FTIR spectroscopy is a molecular analytical technique well suited to identifying common clay minerals contained in soil, such as kaolinite, smectite, and illite, and their heat-related transformations (see Berna et al., 2007 and references therein). In particular, at around and above 500°C the structure of kaolinite is destroyed, and above 700°C the structures of smectite, illite, and mica are destroyed. Presence or absence of these minerals can be determined using FTIR and mFTIR via the observation of IR bands at 915, 1030, 3620, 3650, and 3695 cm^{-1}.

Subsamples of the six archaeological balls, as well as unheated and experimentally heated control samples and experimental balls were analyzed. Loose samples were evaluated in transmission mode using a Thermo-Nicolet Nexus 470 IR spectrometer. Representative FTIR spectra were obtained by grinding a few tens of micrograms of sample using an agate mortar and pestle. About 0.1 mg or less of each sample was mixed with about 80 mg of KBr (IR-grade). A 7 mm pellet was made using a hand press (Qwik Handi-Press, Spectra-Tech Industries Corporation) without evacuation. The spectra were collected between 4000 and 400 cm^{-1} at 4 cm^{-1} resolution. In addition, the six archaeological ball thin sections were mapped by mFTIR using a Thermo-Spectra-tech Continuum IR microscope attached to the spectrometer. Spectra of particles with a diameter of about 150 µm were collected in transmission with a Reflectocromat 15× objective between 2400 and 4000 cm^{-1} at 8 cm^{-1} resolution.

3.5. Microbotanical analyses

Microbotanical residues adhering to the six unwashed balls were collected prior to thin section preparation by adapting a three-step method from published protocols (Pearsall et al., 2004; Perry, 2001). The first step involved brushing and rinsing each clay ball with a clean toothbrush and deionized water (Sediment 1). Each ball was then transferred to a clean beaker and covered with deionized water, placed in an ultrasonic water bath, and sonicated for 10 minutes (Sediment 2). The sonication step was repeated once for each ball by transferring it to a new clean beaker with fresh deionized water and sonicating again for 10 minutes (Sediment 3). After concentrating the residues in 15 mL centrifuge tubes, the entire contents of each tube was mounted on a microscope slide and mixed with a single drop of a 1:1 glycerine/water solution. All of the Sediment 1 fractions contained abundant clay-rich sediments and required an additional CsCl heavy-liquid flotation step (mixed to a specific gravity of 1.8 g/mL to recover starch grains). Each slide was examined under a polarizing light microscope at 400× and all phytoliths and starch grains were counted and photographed.

Phytoliths were extracted from three sediment samples collected in tandem with the clay balls—using microwave digestion, conducted at the University of California, Berkeley Paleoethnobotany Laboratory (Coil et al., 2003). The samples were subdivided into sand and silt-size fractions (10g each) and 100 phytoliths were counted per slide (200 phytoliths per sample), after which the slides were scanned completely for economic taxa (following Piperno, 2006). These were processed in tandem with 33 other archaeological samples from EAC, and 12 control samples collected from test pits in uninhabited areas and a modern Yucatec Maya houselot. The sediments surrounding the clay balls produced the basic background vegetation phytolith assemblage (tropical trees, grass bulliforms, etc.) with very few phytoliths from economic species representing plant food ingredients. In total, there were two forms consistent with maize cobs and leaves [*Zea mays*], respectively; one burned squash rind phytolith [*Cucurbita* sp.]; and a handful of spherical palm forms [Arecaceae]. These results provide an independent line of evidence that the residues adhering to the clay balls are probably not a result of contamination. Previous attempts by the first author to recover starch from EAC and Kiuic sediments proved unsuccessful, likely owing to microbial activity in the humid tropical soils (Haslam, 2004; Torrence and Barton, 2006); therefore, the sediment samples were only processed for phytoliths.

Identifications are based on comparison with published micrographs and modern reference materials. Modern samples were prepared in a separate area of the Boston University Palaeoethnobotany Laboratory and all sampling materials were sterilized by boiling to avoid contamination.

4. Results

4.1. Modal data

The entire clay ball assemblage includes 77 hemispherical to complete balls, and 912 smaller fragments (Table 1). Of the 912 fragments, 89 represent at least a quarter of a ball and are included in the total for the succeeding discussion of modal trends (n = 166).

More than half of the quarter to complete balls (65%) and many smaller fragments contain areas of fire darkening; this includes the interior surfaces of broken balls, which suggests that they continued to be heated or exposed to fire after breaking. Ball shape ranges from spherical to slightly flattened spheres (elliptical in profile) and exterior surfaces are highly irregular, with abundant cracks and pitting indicating expedient preparation. None exhibit evidence of smoothing or application of slips such as those found on pottery in the region (Smith 1971). The clay matrix contains inclusions of quartz, less frequently grog, and occasional black, fine sand-size nodules that petrographic analysis revealed to be Fe nodules.

Four general subcategories were defined that reflect a combination of color, structure, and heat treatment. Category 1 comprises balls with a distinctive orange rim surrounding a buff core that exhibit a moderately cracked structure (n = 29; 17%); Category 2 includes balls with a moderately cracked structure, similar to Category 1, that are solid or mottled orange or peach in color, but that lack a defined orange rim (n = 60; 36%); Category 3 is defined by balls with a reddish-orange exterior and blackened to brown, soft interior, and a massive structure with few cracks (n = 41; 25%). The last subcategory, Category 4, includes reddish-brown or buff balls with a highly cracked structure, that tend to be more friable (n = 36; 22%). There is no discernible relationship between the size of the balls and variation in internal and external color.

4.2. Ceramic petrography

Local control sediments, one experimental ball (fired in the muffle furnace at 700°C for 2 hours), and six archaeological clay balls (Ball 1–6), selected according to their macroscopic modal attributes and category, were processed in petrographic thin section (Fig. 4; Table 2). Specifically, Balls 2 and 6 belong to Category 1, Ball 1 to Category 2, Ball 5 to Category 3, and Ball 3 to Category 4; Ball 4 is an outlier. Overall, the matrix of the local sediment is consistent with that of five of the six balls, especially with regard to color (2.5YR 4/8, Fe-stained clay), organic content, the presence of abundant rounded clay aggregates derived from the original clay matrix, and some quartz silt (Figs. 5a–d). Observations support the hypothesis that the balls were manufactured from a local clay source material, with the exception of Ball 4. In thin section, it became apparent that Ball 4 is a large calcite nodule that probably formed in a water-saturated clay deposit (Fig. 5h). This kind of secondary calcite formation is common in caves and sinkholes found throughout the Yucatán peninsula. The experimental ball was found to be consistent with the archaeological balls (Fig. 5c–d).

Here, the salient petrographic differences are presented for each ball. A compelling feature of Ball 1 is the presence of volcanic ash temper (2%), which appears as elongated slender laths (Figs. 5g) (Spensley-Moriarty 2011). Volcanic ash temper is common throughout Maya area ceramics and was probably imported, since it is unlikely that the northern Yucatán peninsula received any volcanic ash airfall (e.g., Ford and Rose, 1995; Simmons and Brem, 1979; Shepard, 1952). Owing to the hasty manner of clay ball preparation and diversity in raw materials, it is possible that the volcanic ash temper was imported for the production of ceramic vessels and that leftover materials were utilized for clay balls. Trace amounts of volcanic ash temper are also present in Balls 2 and 5.

Balls 2 and 6 have a clearly defined reddish-orange rim (0.5 cm thick) surrounding a buff core. Ball 3 was completely anisotropic and mostly a darkened reddish-brown color, indicating that it became vitrified from exposure to very high temperatures (> 700°C). Ball 5 appeared black in the center, with a buff to reddish-orange outer rim, as a product of charred organic matter contained in the clay-rich sediment used for the preparation of clay balls.

4.3. Firing experiments

4.3.1. Local sediments (control samples) in muffle furnace

The only macroscopically observable changes to the loose, local sediments involved a slight color change from the natural Fe-stained red to bright reddish-orange.

4.3.2. Experimental clay balls in muffle furnace and open fire pit

To summarize the macroscopic observations (Fig. 6), the balls fired in the oven at 550°C for two hours, those fired to flash points of 625°C and 700°C, and all three balls from the open fire pit changed from a deep red (natural) color to bright reddish-orange on the outside and internal rim; the cores turned dark brown to black due to the charring of organic matter dispersed in the clay matrix. The balls heated in the furnace at 550°C for four and eight hours became solid bright reddish-orange throughout the core indicating that all of the organic material was completely oxidized. The ball heated in the furnace at 625°C for four hours produced a bright reddish-orange surface and external rim (0.4–0.5 cm thick) with a buff core (Fig. 6f); the three balls cooked at 700°C (for two, four, and eight hours) resulted in the same color changes, but with a much thinner orange rim (ca. 0.1 cm thick) (Figs. 6g–i).

4.4. FTIR and mFTIR

4.4.1. Unheated and heated local sediments (control samples) in muffle furnace

Representative FTIR spectra of unheated and experimentally heated local sediments are provided in Figure 7. The FTIR spectra from local sediments show strong absorptions of kaolinite-like minerals at 915, 1010, 1030, 3620, 3650, and 3695 cm^{-1}. These absorptions persist to about 500°C. It is necessary to maintain a temperature of 500°C for two hours to destroy the structure of kaolinite, hence the FTIR absorptions of the local kaolinite-like mineral. When heating the local sediments to temperatures ranging from 600 to 700°C, the presence of the OH– absorption at 3620 cm^{-1} indicates that the structure of smectite and mica in the sediment is maintained at these temperatures; however, when heated above 800°C, the absence of the OH– absorption at 3620 cm^{-1} indicates that the structure of smectite and mica has been destroyed.

4.4.2. Experimental clay balls in muffle furnace and open fire pit

As expected from the results obtained from the loose sediments, FTIR analysis indicates a strong but incomplete reduction of the smectite-mica and kaolinite absorptions at 3620, 3650, and 3695 cm^{-1} in the clay matrix of the balls fired above 550°C for two hours. In contrast, in the balls fired at 550°C for four and eight hours, which turned solid bright reddish-orange throughout their cores, the smectite-mica absorption at 3620 cm^{-1} is weak and the kaolinite absorptions at 3695 and 3650 cm^{-1} are absent. Similar FTIR patterns were obtained from the balls heated in the furnace at 625°C for four hours and at 700°C (for two, four, and eight hours) and showing a bright reddish-orange surface and external rim with a buff core (Fig. 6). The FTIR analyses thus suggest that there is no strict correlation among discoloration of the clay matrix, maximum temperature, and mineral composition. Discoloration, in fact, depends on the amount of oxidizable organic matter, temperature, and available oxygen during firing. Thus, similar discoloration can be produced with slightly different combustion conditions.

4.4.3. Archaeological clay balls

FTIR analysis of subsamples scraped from external and internal portions of Ball 1 showed that this ball was not heated homogeneously throughout. Specifically, the material collected from the surface shows IR absorption of mica-smectite at 3620 cm^{-1} but no residual absorptions of kaolinite at 3695 cm^{-1}, suggesting that the temperature reached by the external portion of the ball exceeded 500°C but was below 700–800°C. In contrast, the presence of the IR absorption of kaolinite in the internal portion of the ball suggests that here the temperature never exceeded 500°C.

The analysis of Balls 2 and 6 shows the absence of kaolinite and mica-smectite absorptions suggesting that these two balls were heated homogeneously at temperatures exceeding 700°C, despite the discoloration between the external rim and internal portion of each ball.

Similarly, the FTIR analysis of Ball 3 shows absorption of kaolinite on the surface and in the internal portion suggesting that this ball was heated homogeneously at temperatures below 500°C. The composition of Ball 4 is dominated by calcite and fresh clay, suggesting that it was never heated. Finally, FTIR analysis of Ball 5 revealed a very heterogeneous composition (described in Section 4.4.4).

4.4.4. Mapping by mFTIR

Because of its heterogeneous mineralogical composition, Ball 5 was mapped in detail by mFTIR in order to reconstruct its thermal history. The mapping revealed that several portions had a homogeneous mineralogical composition showing different relative FTIR absorptions of kaolinite and mica-smectite, indicating different heat exposure through the ball. Some areas reflect temperatures lower than 500°C (Fig. 8)

4.5. Microbotanical residues

All six balls produced starch residues (n = 56 starch grains) and one phytolith was recovered (adhering to the balls) (Table 3). The majority of the starch grains were from the sonicated fractions (n = 38), supporting the interpretation that the residues should be attributed to use of the balls rather than to contamination from surrounding sediments.

Maize starch [*Zea mays*] (n = 9) from a hard endosperm variety is most abundant among the diagnostic starch grains. Other diagnostic species include squash [*Cucurbita* sp.], bean [including forms consistent with both *Phaseolus* sp. and *Canavalia* sp.], one grain that is consistent with arrowroot [cf. *Maranta arundinaceae*], and other grains that are probably derived from underground storage organs (based on morphology consisting of elongated oval shapes with off-center hila and clearly defined lamellae commonly found in these plant organs) (Fig. 9), but that have not yet been identified. Ball 4 (the calcite nodule) contained the most starch residue (n = 29); explanations for this remain elusive as starch taphonomy is still imperfectly understood (Henry et al., 2009; Torrence and Barton, 2006). It is possible that calcite provides better conditions for starch adhesion and thus preservation (Goldenberg et al., 2011), or perhaps Ball 4 was treated in a different manner from the clay balls (e.g., FTIR suggests that it was not heated). Some of the recovered starch grains exhibit damage consistent with cooking or other forms of processing (e.g., swelling, loss of features such as lamellae, and reduction or loss of the extinction cross); however, experimental and archaeological case studies demonstrate that starch can survive unaltered even with prolonged exposure to high temperatures (Chandler-Ezell et al., 2006; Henry et al., 2009; Messner and Schindler, 2010; Saul et al. 2012; Zarrillo et al., 2008). Messner and Schindler (2010: 334) concluded that other factors—such as environmental cooking conditions and the order in which plant processing steps are performed—influence the archaeological visibility of ancient starch more significantly than temperature alone.

5. Discussion

Petrographic analysis revealed that of the six archaeological balls belonging to the four categories, two (Balls 2 and 6) had similar petrological characteristics while the other four exhibited highly distinctive characteristics (Fig. 4; Table 2). Subsequent FTIR analysis revealed that the observed differences, especially with regard to color and isotropy, are primarily attributable to differences in firing conditions. The fine fraction for most of the balls contained secondary rounded clay aggregates in the clay matrix, which is consistent with the control samples (Fig. 4a). These rounded clay aggregates are the product of a vertic soil parent material, which is found throughout low-lying areas of the Puuc region (Dunning, 1992; Wilson, 1980) and suggests that the balls were produced from a local clay source. Vesicular voids produced by escaping air bubbles are another common feature among most balls; these indicate that the balls were prepared using wet clay and allowed to dry before firing.

The results of the firing experiments revealed aspects of clay ball preparation and use by the inhabitants of the northwesternmost household at EAC. The observed patterns for the 12 experimental balls provide general parameters for interpreting the firing temperatures, duration, and other behaviors that contributed to the considerable heterogeneity among the archaeological balls (Fig. 6). FTIR data indicate that most, but not all, of the kaolinite clay matrix is destroyed after the balls are fired above 550°C for two hours. Thus, the firing temperatures that resulted in black cores (Category 3) do not produce completely fired balls, which is perhaps a result of some balls being placed away from the hottest part of the fire and/or being used less frequently than others that are thoroughly fired. Category 3 balls represent ca. 25% of the total assemblage, which suggests that firing temperatures regularly exceeded 550°C and/or that the majority of balls were heated for more than two hours, supporting other evidence that they were reused. The remainder of the balls were fired evenly and thoroughly. The most striking aspect of Balls 2 and 6 is the clearly defined reddish-orange rim (0.5 cm thick) surrounding a buff core, which is also present in 17% of the total clay ball assemblage. This pattern of Fe depletion was reproduced in experimental balls fired at 625°C (for four hours) and above, suggesting that temperatures often reached or exceeded 625°C and/or the balls were fired long enough and/or reused enough times to produce these patterns. The color and vitrified structure of Ball 3 (Category 4) was not reproduced through the firing experiments, thus it would likely require repeated exposure to temperatures above 800°C and/or a very long firing time.

Other significant observations include the presence of fire darkening where the open-fired balls came in contact with live embers, a common attribute within the archaeological assemblage. Also, the open firing experiment produced uneven heating with the side of the balls that was exposed to live embers becoming more fired with less carbonized organic material present than the opposite side that was oriented away from the fire. The overall heterogeneity observed within the archaeological assemblage is most likely a product of position in the fire and the number of times each ball was reused.

Considering the quantity and types of starch residues adhering to the fired clay balls—a hard endosperm variety of maize, squash, beans, and root starch—as well as their depositional context outside of a kitchen, we hypothesize that they were involved in plant food processing. Possible forms of processing include grinding or pounding, or more likely cooking. Recent studies have revealed that microbotanical residues from ingredients placed in pit oven cooking installations become dispersed throughout the feature and embedded in cook stones used as heating elements (Thoms et al., 2011). We propose that a similar mechanism is responsible for the residues adhering to the fired clay balls. Ethnographic and ethnohistorical literature for the Maya area describe numerous examples of cooking breads, meats, roots, and other food preparations in pit ovens, often wrapped in maize leaves (or banana leaves today). Today, pit ovens are prepared with stone heating elements, but for the Puuc Maya no such material was readily available; however, the local sediments are full of clay, which could have been used to expediently manufacture clay balls instead. The same solution has been documented in other times and places (e.g., Poverty Point, Çatalhöyük), where humans made use of comparable resources to cook food and/or heat their homes using similar-sized clay balls. Other similarities among modal attributes such as size, shape, surface treatment, fire darkening, etc. for archaeological examples of fired clay balls lend additional support to the interpretation of those from EAC.

6. Conclusion

Our results reveal the history of the production and use of fired clay balls at EAC. They were expediently manufactured in a standardized range of sizes from local clay, either from scraps leftover from pottery production or resources collected from the immediate vicinity of the household. The balls were formed with wet clay and allowed to dry prior to firing, after which they were heated to temperatures consistent with cooking fires (500–700°C). They were burned unevenly, likely depending on their position in the fire; also most were repeatedly reused even after they became cracked or fragmented. Maize, beans, squash, and root crop residues adhering to the balls suggest that they were involved in food processing. The inhabitants of the northwestern EAC household appear to have been using the balls somewhere within the group, and then dumped them behind the kitchen after their primary use life had expired. So far we have not recovered evidence of a hearth or oven; but, considered in their archaeological context among storage vessels, grinding stones, and other culinary implements, we hypothesize that the fired clay balls represent a heating element, most likely involved in cooking food at EAC.

Future research should focus on whether fired clay balls are restricted to the Puuc region, as well as identifying and microscopically analyzing hearths and other combustion features. Additional experimental studies are necessary to explore the hypothesis that the fired clay balls played a role in prehispanic Maya cooking, either for boiling in the pot or baking or steaming in a pit oven.

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Table 1. Summary of modal data for attributes of size, weight, and presence of fire darkening.

Size	n	Mean diameter (cm)	Diameter range (cm)	Total weight (g)	Mean weight (g)	Weight range (g)	Fire darkening* (n)
100%	9	4.3	3.7–5.4	401	44.6	29–72	5
75–99%	21	4.4	3.7–5.3	734	35.0	22–67	13
50–74%	47	4.1	3.5–4.8	1302	27.7	15–48	30
25–49%	89	-	-	1501	16.9	-	46
1–24%	823	-	-	4575	5.6	-	689

* Presence of fire darkening is noted on exposed surfaces of fired clay balls, which includes interior surfaces of broken balls.

Table 2. Summary of modal data and petrographic analysis for Balls 1–6.

Sample	Diam. (cm)	Wt. (g)	Shape	Munsell	Fire darkening	Description
Ball 1	4.1	39	subsphere	5YR 5/6 (uniform peach-orange)	yes	Massive structure with vesicular voids (2%), rare planar voids; porphyric related distribution; granostriated b-fabric; orange in PPL, dark orange-brown in XPL; coarse fraction: volcanic ash (5%), moderately sorted subangular to subrounded quartz fine silt (5%), Fe nodules (2%); fine fraction: rounded clay aggregates in clay matrix
Ball 2	5.4	72	sphere	2.5YR 4/6 (red-orange rim, 0.5 cm thick); 7.5YR 6/4 (buff core)	yes	Abundant vesicular voids (5%), planar voids with Mn staining at boundaries (from water movement through matrix) (5%); porphyric related distribution; granostriated b-fabric; core light brown, rim red-orange in PPL; core dark brown, rim dark red-brown in XPL; coarse fraction: Fe nodules (5%); well-sorted bimodal subrounded quartz fine silt (<2%) and subrounded quartz fine sand (<2%); volcanic ash (<2%); fine fraction: rounded clay aggregates in clay matrix with limpid yellow clay coatings; cf. Ball 6
Ball 3	3.7	42	sphere	2.5YR 4/3 (dark red-brown); 2.5YR 3/6 (thin, partial rim of bright red-brown, 0.4 cm thick)	yes	Very cracked structure with random planar and vesicular voids (20%); anisotropic except at thin red-brown rim; dark brown-black in PPL and XPL; coarse fraction: well-sorted bimodal subrounded quartz fine silt (<2%) and subrounded quartz fine sand (<2%); fine fraction: possibly vitrified clay
Ball 4	4.3	37	elliptical	N/A	yes	Massive structure, no voids; veins of needle-like secondary calcite formation (40%) (weathered) in clay deposit (60%); red-orange clay in PPL, dark red-brown in XPL; coarse fraction: black Fe nodule

						in center (2 × 3mm)
Ball 5	3.9	40	sphere	7.5YR 6/4, 2.5YR 4/6 (buff to red-orange rim); 2.5YR 3/3 (black-brown core)	no	Poor impregnation of resin in center; vesicular voids (2%) and planar voids (2%); porphyric related distribution; granostriated b-fabric; buff to light brown to orange-brown to red-orange rim in PPL, brown core; dark brown in XPL; coarse fraction: Fe nodules (5%); well-sorted bimodal subrounded quartz fine silt (<2%) and subrounded quartz fine sand (<2%); volcanic ash (<2%); fine fraction: rounded clay aggregates in clay matrix with limpid yellow clay coatings
Ball 6	4.5	51	subsphere	2.5YR 4/6 (red-orange rim, 0.5 cm thick); 7.5YR 6/4 (buff core)	no	Abundant vesicular voids (5%), planar voids with Mn staining at boundaries (from water movement through matrix) (5%); porphyric related distribution; granostriated b-fabric; core light brown, rim red-orange in PPL; core dark brown, rim dark red-brown in XPL; coarse fraction: Fe nodules (2%); well-sorted bimodal subrounded quartz fine silt (<2%) and subrounded quartz fine sand (<2%); fine fraction: rounded clay aggregates in clay matrix with limpid yellow clay coatings; cf. Ball 2
Exp. ball	4.1	41	sphere	2.5YR 4/6 (red-orange rim, 0.2 cm thick); 7.5YR 6/4 (buff core)	-	Abundant vesicular voids (5%) and planar voids (2%); porphyric related distribution; granostriated b-fabric; core light brown, rim red-orange in PPL; core dark brown, rim dark red-brown in XPL; coarse fraction: Fe nodules (5%); well-sorted bimodal subrounded quartz fine silt (<2%) and subrounded quartz fine sand (<2%); fine fraction: rounded clay aggregates in clay matrix with limpid yellow clay coatings
Control sediments	-	-	-	2.5YR 4/6	-	Massive structure; porphyric related distribution; granostriated b-fabric; red-orange in PPL; dark red in XPL; coarse fraction: organic material (10%); Fe

						nodules (5%); well-sorted bimodal subrounded quartz fine silt (<2%) and subrounded quartz fine sand (<2%); fine fraction: rounded clay aggregates in clay matrix with limpid yellow clay coatings

Table 3. Summary of microbotanical residues. Samples marked with W = brushed fractions; Z1 = first round of sonicated fractions; and Z2 = second round of sonicated fractions.

Sample no.	n starch	n phytoliths	*Zea mays*	cf. *Z. mays*	*Cucurbita* sp.	*Phaseolus* sp.	cf. *Phaseolus* sp.	cf. *Canavalia* sp.	cf. *Maranta arundinaceae*	cf. USO	Unidentif.
Ball1W	1	-	-	-	-	-	-	-	-	-	1
Ball1Z1	1	1	-	-	-	-	-	-	-	-	2
Ball1Z2	-	-	-	-	-	-	-	-	-	-	-
Ball2W	-	-	-	-	-	-	-	-	-	-	-
Ball2Z1	2	-	-	-	-	-	-	-	-	-	2
Ball2Z2	-	-	-	-	-	-	-	-	-	-	-
Ball3W	8	-	-	3	-	-	-	-	-	-	5
Ball3Z1	5	-	-	2	-	-	-	-	-	-	3
Ball3Z2	1	-	-	-	-	-	-	-	-	-	1
Ball4W	6	-	-	-	-	-	-	-	-	-	6
Ball4Z1	20	-	8	1	1	1	1	2	1	1	4
Ball4Z2	3	-	1	-	-	-	-	-	-	-	2
Ball5W	1	-	-	-	-	-	-	-	-	-	1
Ball5Z1	2	-	-	-	-	-	-	-	-	1	1
Ball5Z2	-	-	-	-	-	-	-	-	-	-	-
Ball6W	2	-	-	-	-	-	-	-	-	-	2
Ball6Z1	2	-	-	-	-	-	-	-	-	-	2
Ball6Z2	1	-	-	-	-	-	-	-	-	-	1
Totals	56	1	9	6	1	1	1	2	1	2	33

Figure captions

Fig. 1. Plan view of the EAC hilltop with the residential North Group and residential/civic-ceremonial South Group. Each grid square measures 2 × 2 m. Map of the Yucatán peninsula showing the location of EAC (inset).

Fig. 2. Plan view drawing of the investigated structures and floor assemblages in the nothwestern patio group. From north to south: Structure S2865E3225, related to food preparation; Structure S2870E3225, a vaulted residence also used for storage and containing ancestral burials; and S2880E3230, a food-preparation and storage structure (kitchen) with the location of the burned clay ball deposit marked on the southeastern, exterior corner. Other floor assemblage materials include reconstructable ceramic storage, cooking, and serving vessels; imported chert and obsidian implements; grinding stones (numerous *manos* and *metates*, one mortar and pestle), a bark beater, and personal adornments.

Fig. 3. Photograph with examples of complete or nearly complete fired clay balls.

Fig. 4. Macroscans of thin sections for the six balls subjected to microanalyses: a) Ball 1; b) Ball 2; c) Ball 3; d) Ball 4 (calcite nodule); e) Ball 5; and f) Ball 6. The large slides measure 7.5 × 5.1 cm and the small slide (d) is 4.6 × 2.7 cm.

Fig. 5. Micrographs of petrographic thin sections taken at 4× (a–d) and 10× (e–h) magnification: a) Ball 6: secondary rounded clay aggregates and vesicular voids in plane-polarized light (PPL).

Also note the color change at the boundary of the buff core and reddish-orange outer rim; b) Ball 6 in cross-polarized light (XPL). Note the limpid yellow clay coatings surrounding the rounded clay aggregates (indicated by arrows); c) Experimental clay ball in PPL; d) Experimental clay ball in XPL; e) Secondary rounded clay aggregates in the reference sediments from test pit 1 in PPL; f) Reference sediments from test pit 1 in XPL; g) Volcanic ash temper from Ball 1 in PPL (indicated by arrows); and h) Ball 4, calcite nodule in PPL.

Fig. 6. Scanned cross-sections of experimentally fired clay balls. a–i) Cooked in the muffle furnace at the following temperatures and durations: a–c) 550°C for 2, 4, and 8 hours; d) 625°C flash point; e) 700°C flash point; f) 625°C for 4 hours; g–i) 700°C for 2, 4, and 8 hours. j–l) Cooked in the open firepit for 2, 4, and 8 hours, respectively.

Fig. 7. FTIR spectra from experimentally heated local sediments show strong absorptions of kaolinite-like minerals at 915, 1010, 1030, 3620, 3650, and 3695 cm^{-1}

Fig. 8. FTIR map of Ball 5 showing variation in firing temperatures across the ball. (Left) Letters D, F, G, H, and I correspond with the boundaries of different FTIR spectra. (Right) Color coding based on the letters, with red representing areas exposed to the highest temperatures (above 550°C) through light green representing the lowest temperatures (the side oriented away from the fire).

Fig. 9. Micrographs of diagnostic starch grains recovered from burned clay ball residues: a–d) *Zea mays* in PPL and XPL; note the compression facets from tight packing of grains diagnostic

of hard endosperm varieties; e–f) *Phaseolus* sp. in PPL and XPL; g–h) *Cucurbita* sp. in PPL and XPL; i–j) Unidentified underground storage organ (USO) starch in PPL and XPL; k-l) cf. *Maranta arundinaceae* in PPL and XPL. Each micrograph measures 55 μm on a side.

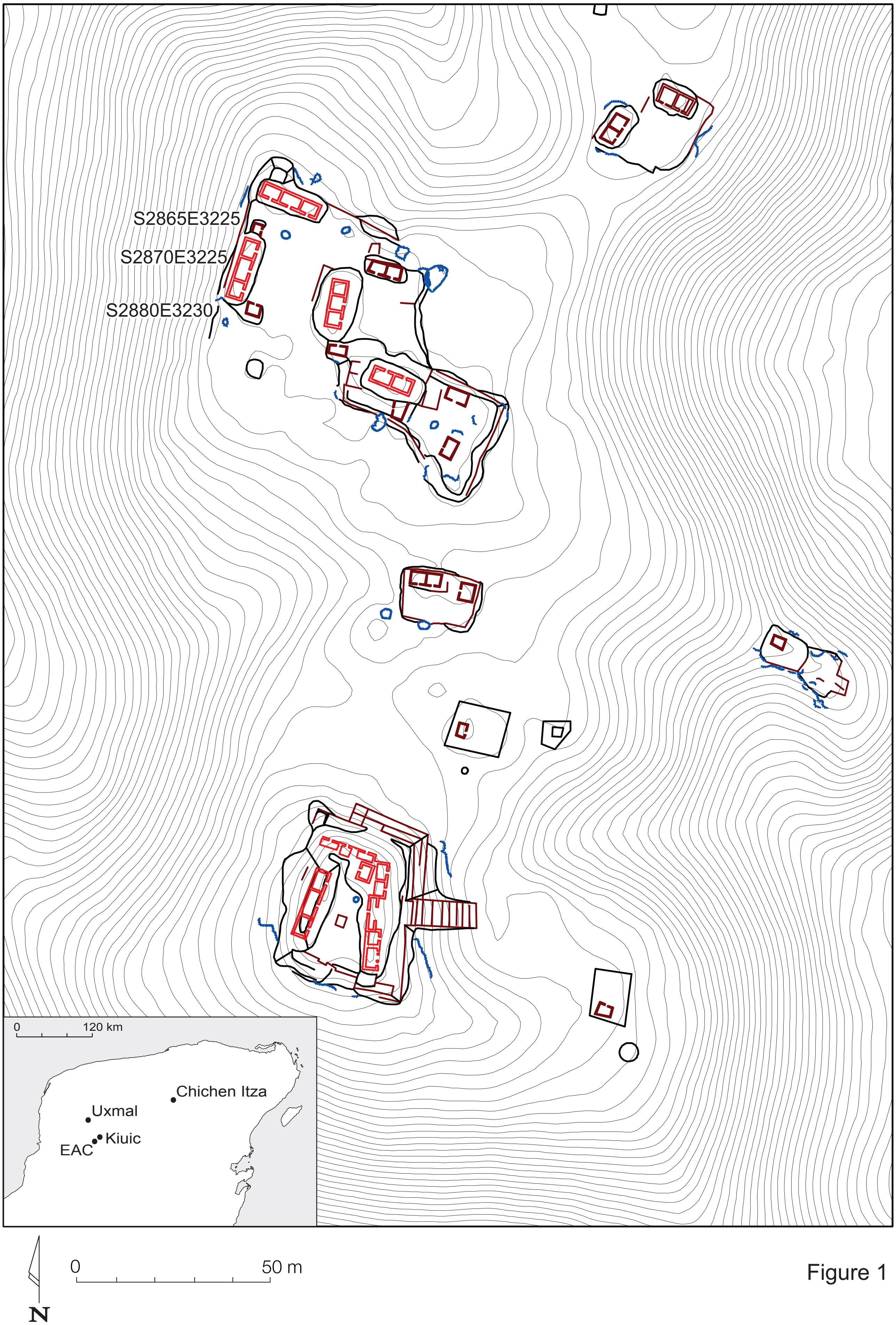

S2865E3225
S2870E3225
S2880E3230
0
120 km
Chichen Itza
Uxmal
Kiuic
EAC
N
0
50 m

Figure 1

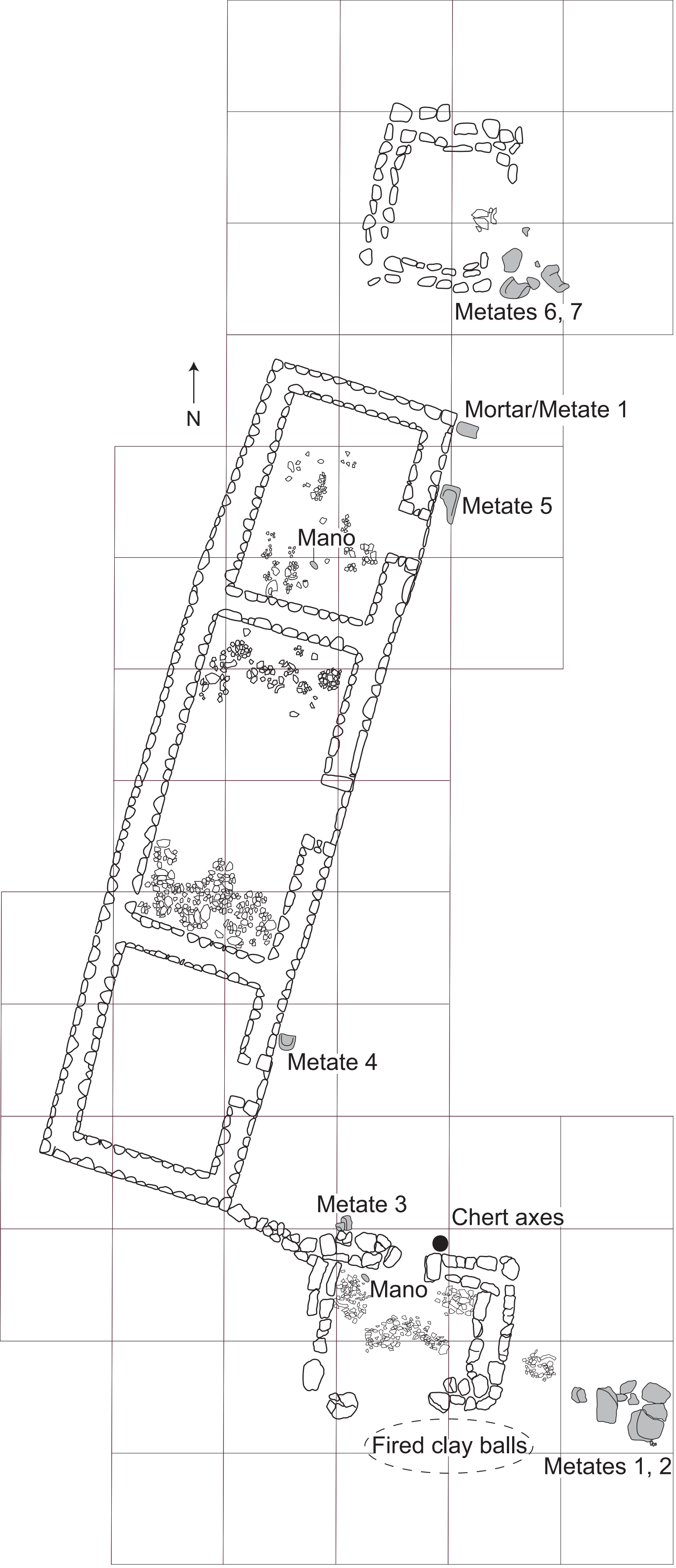

Metates 6, 7
N
Mortar/Metate 1
Metate 5
Mano
Metate 4
Metate 3
Chert axes
Mano
Fired clay balls
Metates 1, 2

Figure 2

Figure 3

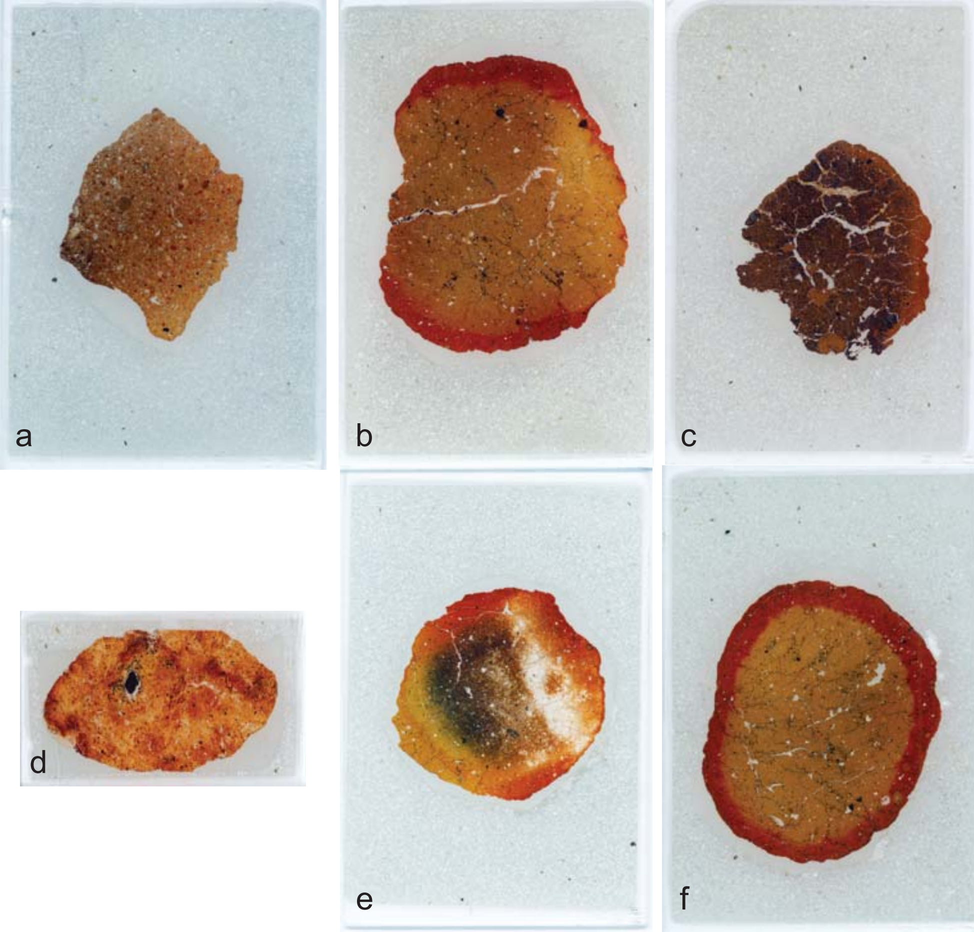
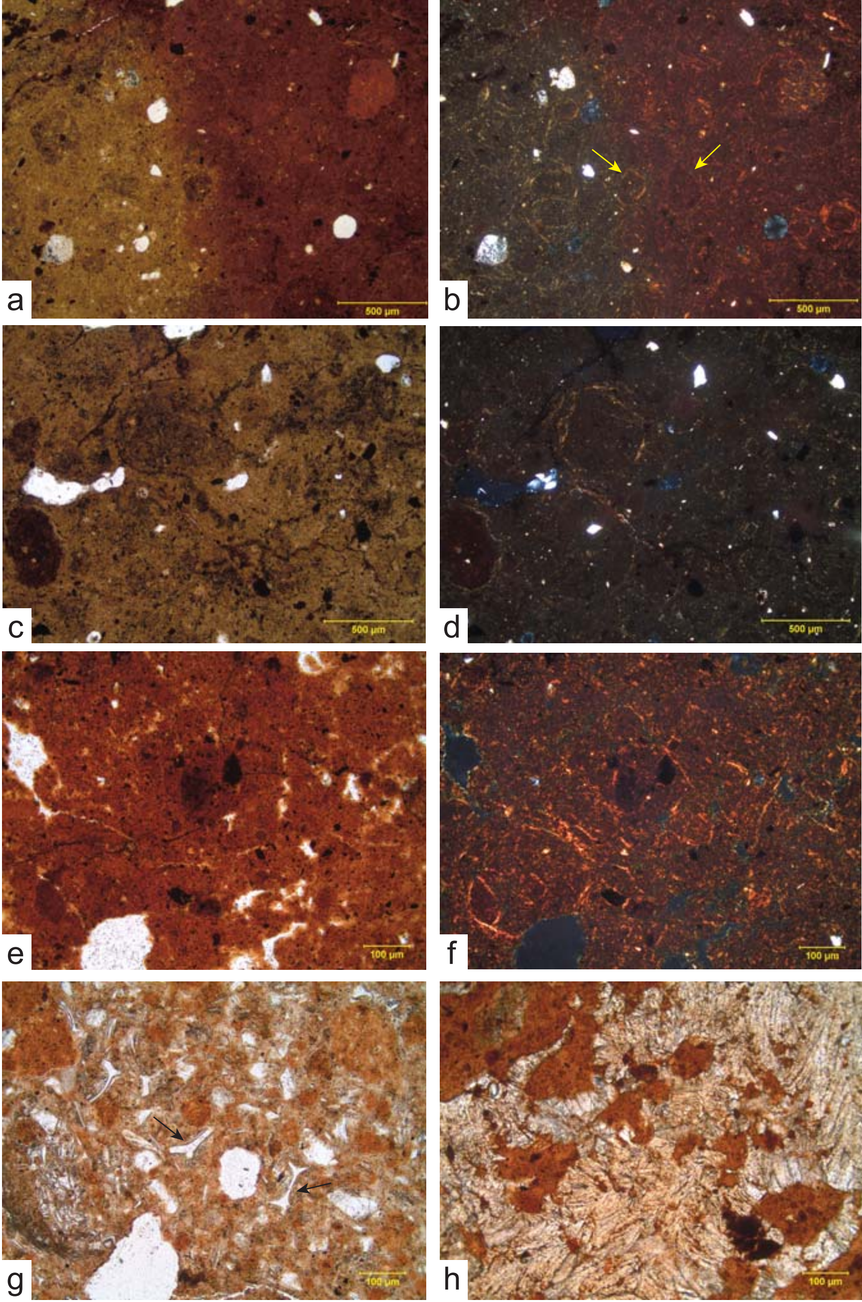


Figure 4


a
500 µm
b
500 µm
c
500 µm
d
500 µm
e
100 µm
f
100 µm
g
100 µm
h
100 µm

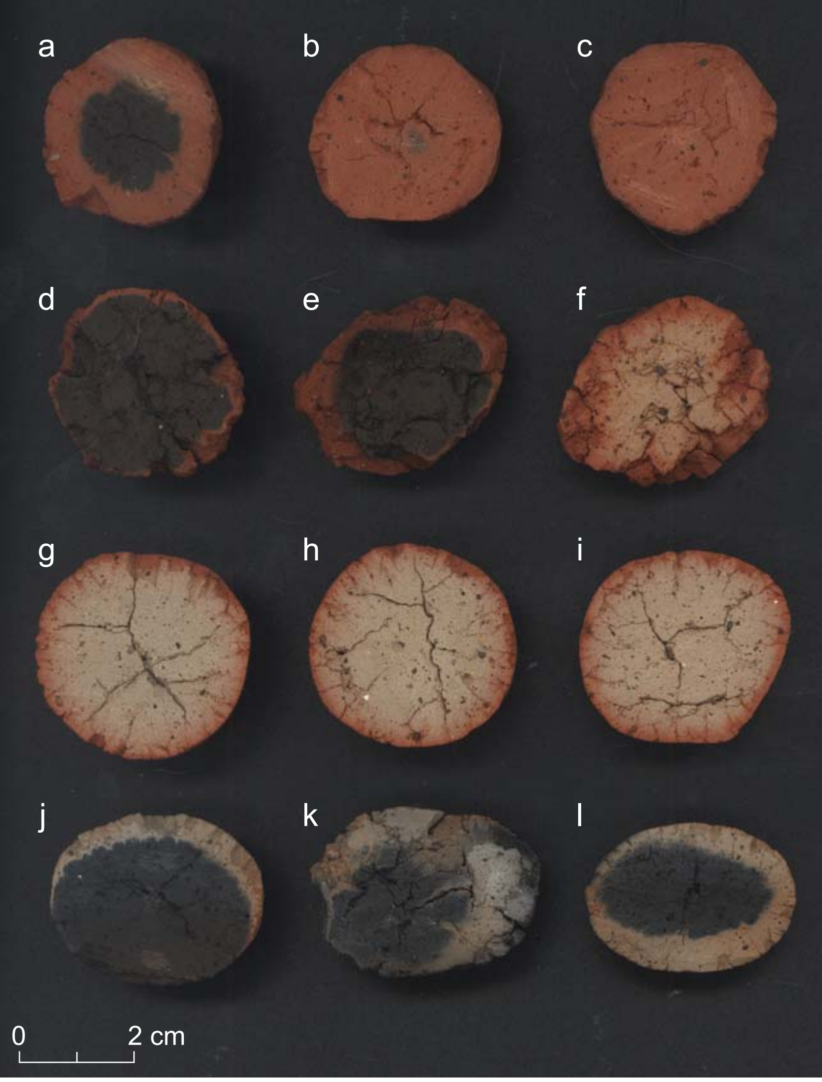
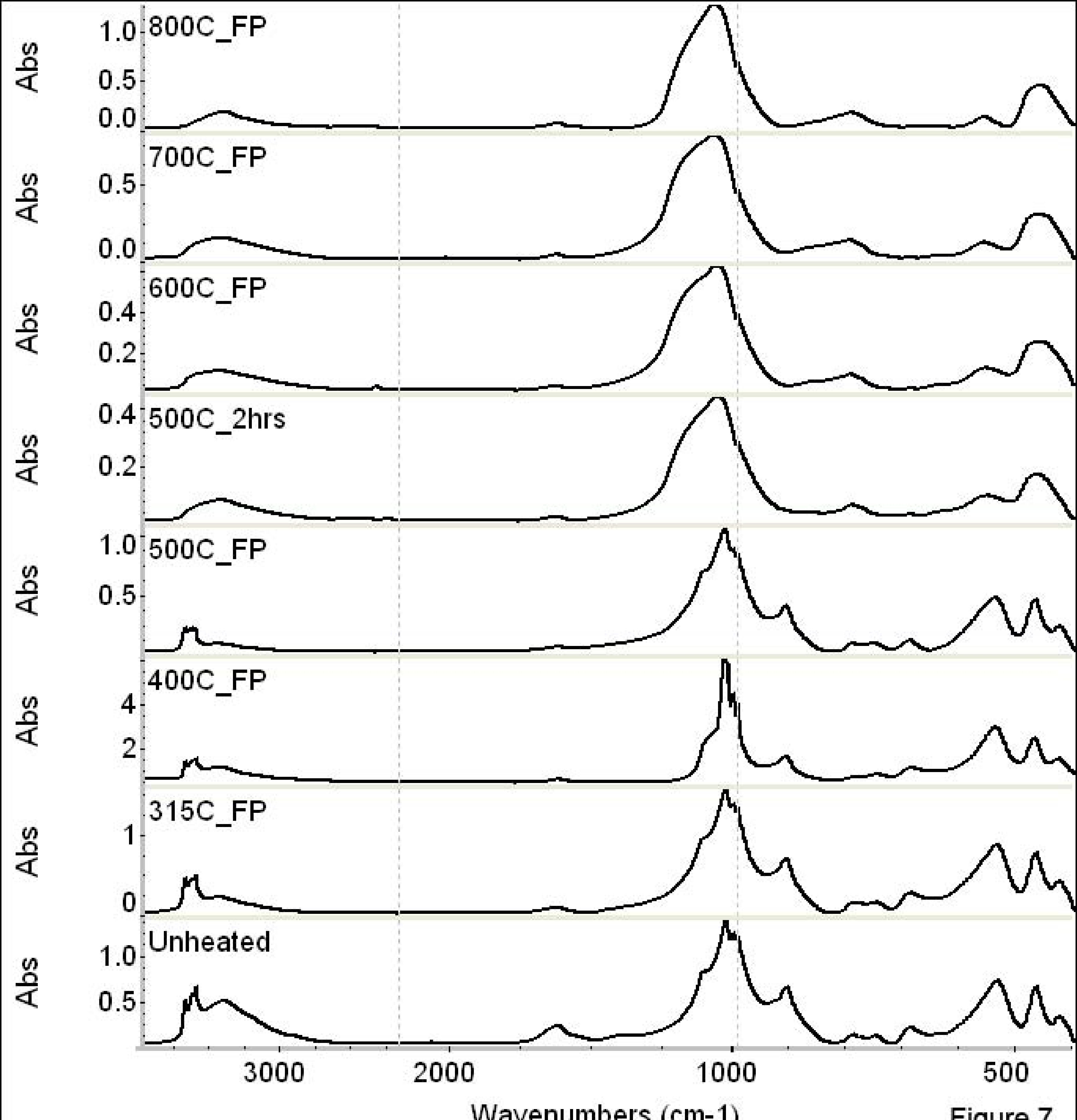


Figure 6



800C_FP
700C_FP
600C_FP
500C_2hrs
500C_FP
400C_FP
315C_FP
Unheated
Abs
1.0
0.5
0.0
0.4
0.2
4
2
1
0
3000
2000
1000
500
Wavenumbers (cm-1)

Figure 7

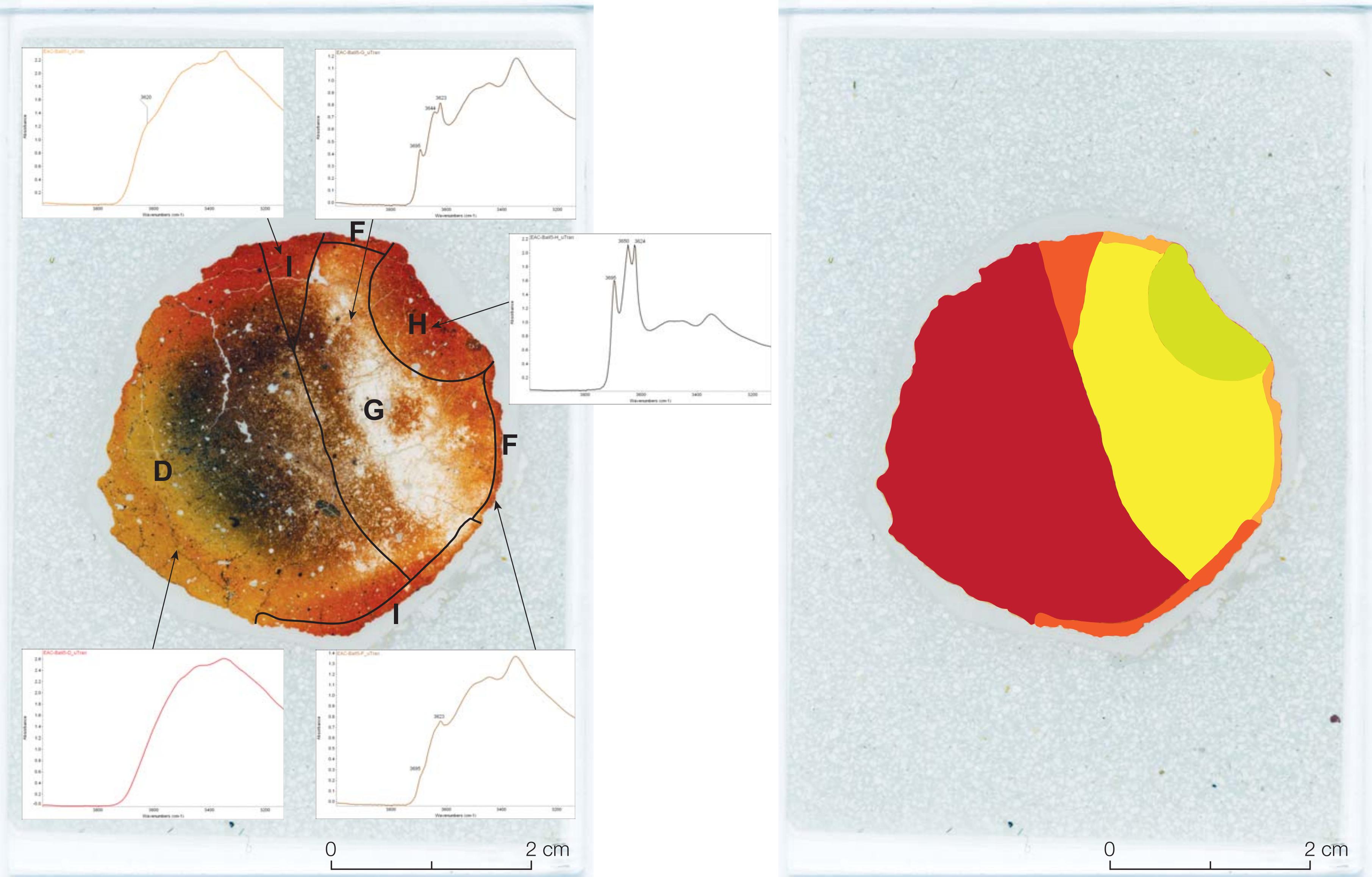


Figure 8

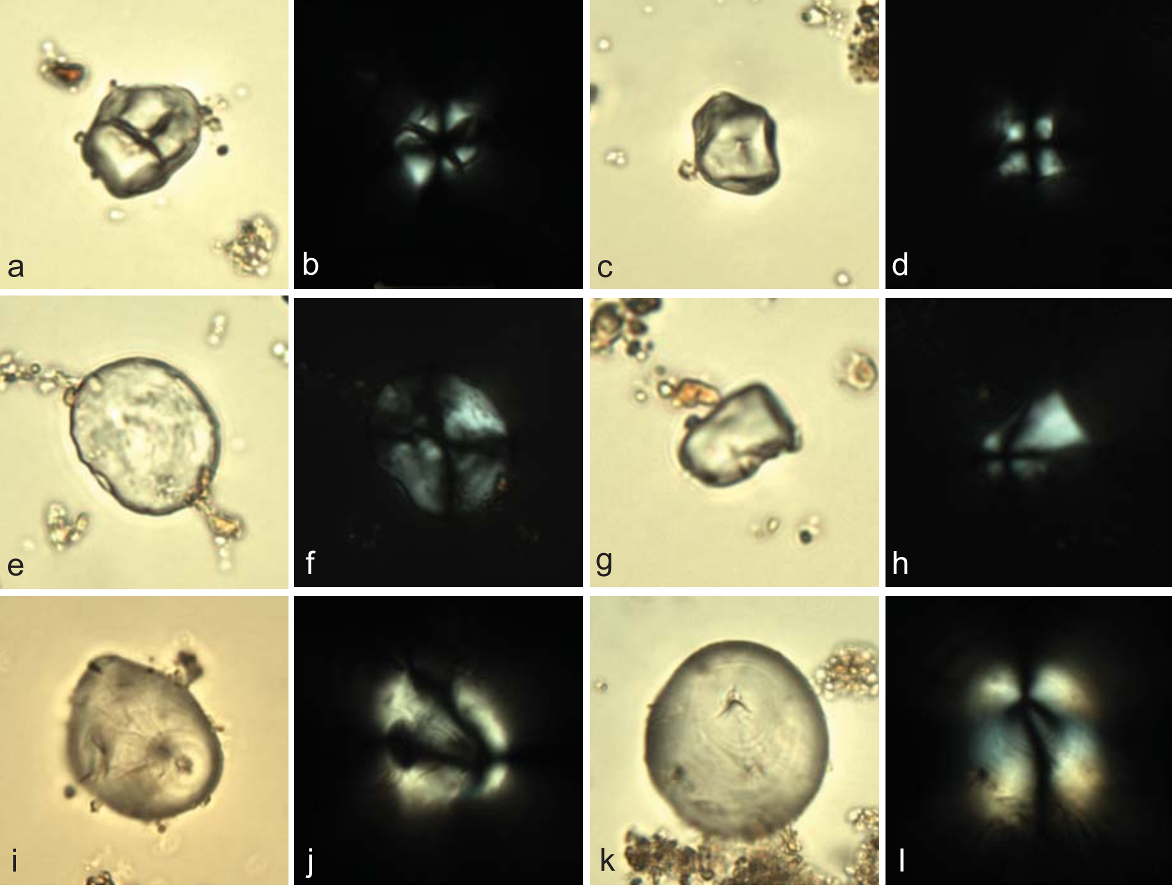


Figure 9