

Baking Geophytes and Tracking Microfossils: Taphonomic Implications for Earth-Oven and Paleodietary Research

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Abstract Archaeologically oriented starch-granule and other plant-food microfossil research contribute to human subsistence studies primarily through analysis of residue adhering to plant processing tools. Little is known about whether or how plant-food microfossils may be present in remains of ancient earth ovens and other cooking facilities. Earth ovens with rock heating elements are found worldwide, especially in savannah and fuel-poor regions; they date to about 30,000 and 9,000 years old in the Old and New Worlds, respectively. Earth-oven baking is a cooking technology that effectively increases the availability of food in a given area by affording nutritional access to difficult-to-cook or toxic plant foods that would otherwise be indigestible. It effectively increases a landscape's capacity to support population growth. Conventional-oven and lab-oven baking experiments assess the potential of ancient earth ovens to yield identifiable microfossils of underground storage organs (USOs) baked therein. During 15 min to 12 h of baking at 135–150 °C, identifiable and degraded USO microfossils accumulated as part of baking residue on cloth coverings, leafy packing materials, the inside of the containers, and on suspended microscope slides. Results of these taphonomic experiments indicate that an abundance of microfossils, including starch granules, phytoliths, raphides, and plant tissue, are emitted from USOs during the baking process. As hypothesized, these microfossils should be mobilized and dispersed in earth ovens *per se* during baking, primarily via liquid and vapor forms of water. Illuviation and other transformation processes are expected to redeposit baked, yet still identifiable, plant-food microfossils on heating-element rocks.

Keywords Starch · Raphides · Phytoliths · Microfossil taphonomy · Earth oven · Fire-cracked rock · Geophytes · Hunter-gatherer diet · Residue analysis · Paleodiet

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Introduction

The archaeological importance of earth ovens with rock heating elements and geophytes, also known as plants with underground storage organs (USOs), derives from key roles they played in the development and evolution of cooking technology. Many parts of the world, especially savannah and fuel-poor regions, had and have edible wild geophytes that are rich in carbohydrates, abundant, readily accessible, and sustain long-term exploitation (Thoms 1989, 2008a). When found in proximity to adequate supplies of rocks and fuel, such places tend to be targeted by hunter-gatherers. Baking geophytes, as well as many other plant and animal foods, in underground ovens for a few hours to several days increases their digestibility and caloric yield (Konlande and Robson 1972; Peacock 2008; Wandsnider 1997; Wrangham 2009). Accordingly, earth-oven baking is a strategy that effectively increases food availability in a given area by transforming otherwise nutritionally poor or inedible foods into edible forms, thereby supporting population growth (Thoms 1989, 2003).

Remains of earth ovens with rock heating elements are among the most globally widespread and abundant of archaeological features (Black and Thoms 2014). Ethnographic and ethnohistoric accounts attest to how these underground baking facilities were built and used (Fig. 1) (e.g., Driver and Massey 1957). Archaeological investigations reveal that they were used in the Old World by 30,000 uncalibrated radiocarbon

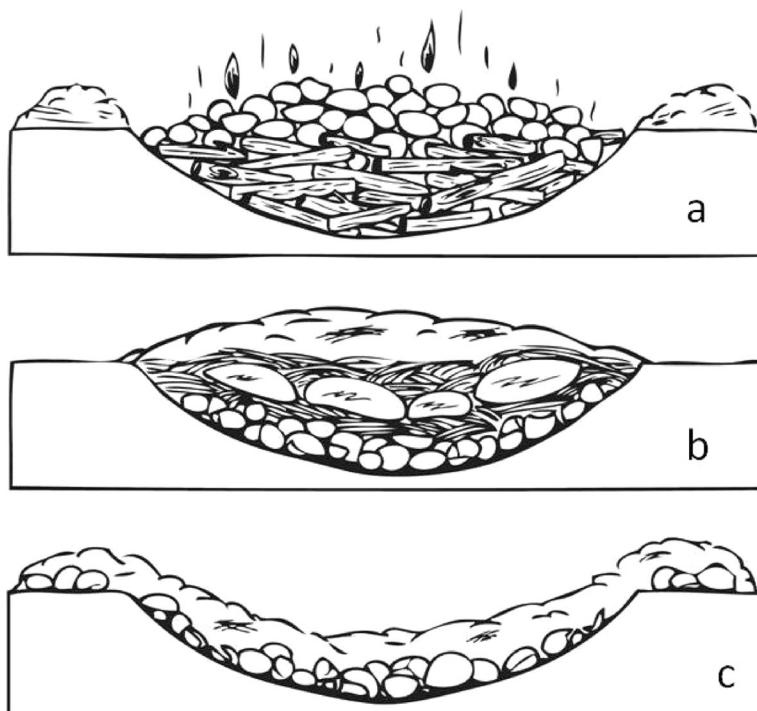


Fig. 1 Sketches of generic earth oven cross sections: **a** firing stage using wood fuel to heat cooking stones, **b** baking stage with food packets between layers of green-vegetation packing material, and **c** abandonment stage after removal of food and decomposition of packing material (modified from Thoms 1989, Fig. 21, p. 268)

years before present (B.P.) and in the New World by 9,000 B.P. (Black and Creel 1997; Dogome 2000; Movius Jr 1966; Thoms 2009; Torrence *et al.* 2004). As abundant and relatively resistant to pedoturbation processes as ancient earth ovens are (Thoms 2007), organic preservation conditions tend to be such that remains of macrofossil-size geophytes or other plant foods baked therein are seldom recovered.

It is the significance of finding direct evidence for ancient diets, coupled with the rarity of recovering identifiable, charred plant-food remains (i.e., macrofossils), that impels archaeologists to search for microfossil evidence (e.g., Perry 2005; Piperno *et al.* 2009). What further beckons archaeologists to plant-food microfossils is that they are far more prevalent than macrofossils and are more likely to be preserved and discovered (Haslam 2004). Hundreds of thousands of microfossils may be compressed into cracks and crevices when plant foods are ground, pounded, scrapped, or otherwise forcefully contacted with a mano, pestle, or other pounding/grinding stones. Some of those, including starch granules, survive degradation processes in identifiable forms for millennia, although the precise mechanisms and chemical processes remain poorly understood (Messner 2011, p. 53). Judging from the densities of starch granules calculated for several species of domestic yam (*Dioscorea* spp.)— $7.14\text{--}621.3 \times 10^7$ granules/g dry weight—(Riley *et al.* 2006), billions of microfossils may be involved every time a few dozen or more kilograms of wild, starch-rich USOs are baked in an earth oven. Calcium oxalate crystals and phytoliths are similarly present in many wild plant foods (Piperno 2006).

Herein, we contribute to archaeologically relevant microfossil research by presenting results of experiments designed to track raw geophyte microfossils—starch granules, phytoliths, calcium oxalate crystals, and plant tissue—through the baking process and into residue deposits. We focus on starch granules. Our research addresses a taphonomically oriented question: *Is it reasonable to expect to find microfossil evidence of plant foods in the remains of ancient earth ovens wherein those foods were baked?* Specifically, we seek to ascertain whether and, if so, how USO microfossils are released during the baking process *per se*. Toward those ends, we baked several species of wild geophyte bulbs and taproots and analyzed residue deposited in glass and ceramic cooking containers, on leafy packing material encompassing the USOs, and on microscope slides suspended above the USOs.

In the absence of identifiable plant-food macrofossils, as is the case with the vast majority of cooking facility remains around the world, microfossils therein may provide equally direct evidence of past foodstuffs. As such, the scientific utility of plant-food microfossil studies is their potential to yield reliable diet-related data that efficiently and effectively supplement or complement macrofossil records (Bryant 2007a). Knowledge about the nature and mobility patterns of plant-food microfossils in controlled oven-baking environments is archaeologically important because it provides a basis for generating expectations about how and where we should find food residues within remains of ancient earth ovens.

Background

Geophytes are plants that bear renewal buds underground (i.e., USOs) as bulbs, corms, tubers, root nodes, taproots, etc. (Raunkiaer 1934). Artifacts of ultimate interest for the

present study are once-hot rocks—cooking stones—that formed heating elements in earth ovens. Archaeologists often refer to these stones as fire-cracked rocks (FCR), fire-altered rock, fire-modified rock, burnt rock, and sundry-related terms (Jackson 1998). In other systemic realms, cooking stones served as griddles as well as in stone boiling and pit steaming (Thoms 2008b). We use the term “cook-stone technology” in reference to processes employed in the procurement, utilization, and discard of rocks that served as heating elements for cooking food (Thoms 2003).

Paleodietary Research Context

Given a working assumption that earth-oven cookery effectively enhances carrying capacity, a marked increase in the use of earth ovens in a given region may signal what Mark Cohen (1977) called a “food crisis in prehistory.” In western North America, ethnographic and archaeological data attest to oven-baked, carbohydrate-rich geophytes and desert succulents (e.g., agave, sotol, and yucca) being significant components of hunter-gatherer and agriculturalist diets (Black and Creel 1997; Leach et al. 2006; Thoms 1989, 2008b; Wandsnider 1997). Baking plant foods in earth ovens with rock heating elements spanned diverse ecological regions; it was well underway by 8,000 B.P. and increased thereafter, sometimes in relatively punctuated fashions that Thoms (2008a) terms “preagricultural carbohydrate revolutions.”

Development and proliferation of earth-oven cookery may have biological implications as well. For example, oven baking renders plant and animal foods softer (i.e., more easily masticated) and may have contributed significantly to the evolution of smaller teeth and related changes in cranial morphology in parts of the Old World during the late Pleistocene (Brace 1967, 1980, 2005; Brace et al. 2008). Recent DNA evidence indicates that biological evolution rather than migrations *per se* likely accounts for cranial-shape differences between the most ancient Americans and American Indians today (Chatters et al. 2014). Accordingly, earth-oven cookery and increased consumption of baked geophytes may be plausible candidates for fostering such evolutionary change in the New World as well.

Geographic and ethnic variations in consumption of starch-rich domestic cereal crops have been linked to the evolution of human amylase gene copy number variation and, hence, our ability to digest starch-rich foods (Perry et al. 2007). Further research is warranted to ascertain whether worldwide increases in carbohydrate and fat consumption prior to the onset of intensive agriculture may have been accompanied evolutionary changes, perhaps in terms of craniofacial shape as well. It has also been argued that development of diabetes may be linked to a shift away from consuming wild geophytes rich in complex carbohydrates, typical of those baked in earth ovens with rock heating elements, and toward marked increases in consumption of processed foods, especially fats and domestic cereals (Wandsnider 1997).

Homo sapiens, regardless of timeframe, were and are effectively full-time cooks (Petruglia 2002; Wrangham 2009). While our Old World ancestors cooked food in, on, and above hot coal fires more than 150,000 years ago (Klein and Edgar 2002; Stiner et al. 2011), they seldom, if ever, used purposely heated stones for cooking (e.g., Soler Mayor 1996). Hot-rock cookery in the Old World emerged among *H. sapiens* by the time Neanderthals, predominately meat eaters, became extinct some 30,000 years ago (Dogome 2000; Mellars 1996; Movius Jr 1966; Piperno et al. 2004; Straus 2006;

Thoms 2009; Torrence *et al.* 2004). While Neanderthals probably consumed starchy plant foods, debate remains concerning the degree to which they were cooked (Collins and Copeland 2011; Henry *et al.* 2011b).

Use of rock heating elements in cooking, arguably a *H. sapiens sapiens* hallmark, conserved fuel and facilitated prolonged baking and boiling, which was necessary to render some foods readily digestible and more nutritious, including animal fat and geophytes (Gott *et al.* 2006; Samuel 2006; Thoms 1989, 2003, 2009; Wandsnider 1997). The cost of these ostensible benefits includes increased labor compared to rockless cookery, especially for women and children, as is widely documented in ethnographic records. Available evidence suggests that cook-stone technology was most commonly used in cooking meats/fats in northern climes (Brace 1967; Movius Jr 1966; Nakazawa *et al.* 2009; Nelson 2010) and for plant foods in warmer settings (Dogome 2000; Torrence *et al.* 2004).

Hot-rock cookery, and arguably the intensive use of plant foods, had been underway in the Old World for more than 10,000 years when groups of immigrants made their way to North America. Interestingly, however, FCR is almost never found at Clovis-age or earlier Paleoindian sites (Hammatt 1976; Petraglia 2002; Reeves 1990; Speth *et al.* 2013; Willey and Phillips 1958; Wissler 1940). Although there are very few archaeologically documented Paleoindian cooking fires of any kind, it is reasonable to conclude that surface hearths were an integral component of every Paleoindian encampment and a focal point of cooking and other familial activities. Ethnohistoric data clearly support this contention insofar as meat, fish, shellfish, and plant foods, including geophytes, were cooked routinely in surface hearths without the aid of any cooking stones (Thoms 1989, 2008b; Wandsnider 1997).

Among the oldest—11,000–10,000 B.P.—evidence reported for hot-rock cookery in North America are FCR features in central Alaska at the Moose Creek site (Pearson 1999), in central Texas at the Wilson-Leonard site (Guy 1998), and in northwest Alabama at Dust Cave (Homsey 2009). Cook-stone technology spread rapidly, and by 8,000 B.P., rock-filled earth ovens were probably in use throughout North America. In much of western North America, geophyte exploitation and earth-oven cookery intensified substantially between 4,000 and 2,000 years ago as evidenced by the increase in the number of earth ovens, many of which have yielded charred lily family bulbs (Acuña 2006; Black and Creel 1997; Boyd *et al.* 2004; Thoms 1989, 2008a). Proliferations of earth-oven technologies indicate a major intensification-oriented shift—from wild animal foods to wild plant foods—in the diet of Native Americans during the early Holocene (cf. Binford 2001).

By identifying taphonomic patterns of geophyte microfossil mobilization, deposition, weathering, and other transformation processes in cooking facilities, new doors are opened toward learning about ancient human diets, land-use patterns, and related sociocultural issues, including feasting and gender roles. Microfossil evidence of paleodiets also will prove useful in generating independent data for assessing hypotheses about the evolution of cranial shape and subsistence patterns around the world (e.g., Binford 2001; Brace 2005; Brace *et al.* 2008; Chatters *et al.* 2014; Leach *et al.* 2006; Messner 2011; Pennisi 1999; Perry *et al.* 2007; Wrangham 2009). Our own research interests include the application of microfossil analyses to assess ideas about the onset of preagricultural carbohydrate revolutions in south-central North America (Laurence *et al.* 2011; Thoms 2008a; Thoms *et al.* 2011).

Earth-Oven Cookery

Ethnographic and ethnohistoric accounts attest to substantial variation in earth oven construction and use (e.g., Black and Creel 1997; Driver and Massey 1957; Ellis 1997; Haslam and Crowther 2009; Kumar and Aalbersberg 2006; Loy 1994a; Messner 2011, p. 120; Messner and Schindler 2010; Peacock 2008; Smith et al. 2001; Stark 2002; Thoms 1989, p. 179–120, 223–227, 264–270; Wandsnider 1997). Nonetheless, generalizations are readily derived from an array of information about earth ovens with rock heating elements (Fig. 1): (1) Although meat, fish, and shellfish were cooked in ovens, tens to hundreds of kilograms of plant foods, especially geophytes and desert succulents (e.g., agave, sotol, yucca, prickly pear), were most commonly baked in these features; (2) smoldering coals and hot rocks in the heating element typically formed the bottom layers in the oven pit; (3) food items were almost always packed between layers of green vegetal material that provided additional moisture during the baking process and protected the food from being instantly burned by the red-hot rocks or being coated by sediment; (4) the resulting low mound of packing material and food was then covered with earth, and in some cases, a fire was built atop it; (5) packing material, along with the raw food itself, usually contained enough water to create an adequately moist baking environment, although water was sometimes added through a hole in the earthen cover to maintain sufficient moisture; and (6) after baking for the requisite time, the earthen cover, the upper layer of packing material, and the food(s) were removed, leaving the underlying packing material and rock heating element relatively intact (Black and Thoms 2014; Thoms 2008b).

For a more detailed review of these and other aspects of ethnographically and nutritionally documented earth-oven cookery, see Wandsnider (1997). Her discussions call attention to the concept that carbohydrates in raw food respond in similar fashions to cooking, regardless of when or where plants grow, an observation that explains many of the worldwide similarities in cook-stone technology. She also notes that baking-related water loss curtails spoilage during storage by limiting the amount of moisture available to microorganisms (Wandsnider 1997, p. 5, 10).

Camas (*Camassia quamash*) bulbs from the Northern Rocky Mountains of central Idaho lost 44 % of their fresh weight after baking in a traditional Nez Perce earth oven for 48 h (Konlande and Robson 1972). After baking for only 30 min in a conventional household oven at 200 °C (392 °F), the moisture content of sweet potato, yam, taro, and cassava was reduced 9–14.8 % (Bradbury et al. 1988). Cassava and taro tubers lost 10.1 and 17.4 % of their weight, respectively, when baked in an earth oven for 1.25 h. Most of the weight loss was from water and attributed to evaporation and “dripping” (Kumar and Aalbersberg 2006, p. 303–304). As per discussions that follow, baking-related water loss plays the key role in the mobilization and deposition of geophyte microfossils.

Plant-Food Microfossil Analysis

Starch granules are glucose polymers formed within chloroplasts (i.e., specialized cytoplasmic bodies containing chlorophyll) of green plants and amyloplasts (i.e., specialized bodies containing one or more starch grains) in USOs, seeds, sporocarps, and to a lesser extent in leaves and stems (Field 2008). Phytoliths, as the term is used

here, are siliceous bodies that form within plants (Piperno 2006, p. 1). Researchers who define phytoliths broadly (e.g., Esau 1965) consider raphides (i.e., needle-shaped crystals made of the biomaterial calcium oxalate) and other calcium oxalate crystals, to be among the phytoliths. We follow Crowther (2009), however, in discussing calcium oxalate crystals as a separate class of plant biominerals based on their elemental composition.

The utility of archaeologically oriented microfossil research is well established (Bruer 1976; Bryant 1974, 2007a; Dering and Shafer 1976; Jones and Bryant 1992; Loy 1994b, Loy *et al.* 1992; Piperno 2006; Shafer and Holloway 1979; Torrence and Barton 2006). Starch-granule and phytolith studies are now among the mainstays for investigating origins of agriculture (Bryant 2007b; Piperno *et al.* 2009; Perry 2007). In combination with tool use-wear studies, macrofossil, and chemical analyses, starch studies also have made forays into roles of wild plant foods used by ancient hunter-gatherer populations (e.g., Chandler-Ezell *et al.* 2006; Cummings 1994; Messner 2011, p. 55–57; Odell 2004; Perry 2004, Perry 2005, Perry 2010; Piperno 2006; Piperno *et al.* 2004).

Other archaeologically relevant studies contain information about microfossil preservation conditions (e.g., Barton 2009; Haslam 2004; Langejans 2010), recovery and processing techniques (e.g., Coil, *et al.* 2003; Fullagar 2006; Horrocks 2005), taxon identification (e.g., McNair 1930; Messner 2011), and hazards of misidentification and contamination (e.g., Haslam 2006; Laurence *et al.* 2011). Much of the relevant plant-microfossil taphonomy literature falls within research spheres, including botanical and soil sciences, which are outside archaeology's routine viewscapes (cf. Haslam 2004).

Extraction and identification of starch granules and phytoliths on stone and wooden tools are firmly entrenched as a method for assessing which plants were ground, pounded, chopped, and cut with what tools (Chandler-Ezell *et al.* 2006; Henry *et al.* 2012; Nugent 2006; Odell 2004, p. 159–165; Piperno 2006; Perry 2004; Torrence and Barton 2006). Messner (2011, p. 40–61) provides a detailed review of archaeologically oriented starch-granule research. The utility of calcium oxalate raphides in archaeologically oriented microfossil research is less established. In general, raphides have too many inter-taxa similarities and too much intra-taxa variation in size and shape to be diagnostic of most plant species. However, some plants foods, for example, members of the Araceae family (e.g., aroids, including taro, *Colocasia esculenta*), may be identified by their unique raphid morphologies (Crowther 2009). Jones and Bryant (1992) determined that it was possible to identify individual species of *Opuntia* (cactus) based on size and morphology of their druse-shaped calcium oxalate crystals.

Starch granules, phytoliths, and other microfossils are also embedded in calculus deposits on human teeth and those of other plant-eating animals. Archaeologists have used plant-microfossil analysis of calculus as a direct assessment of paleodiets (e.g., Dudgeon and Tromp 2012; Hardy *et al.* 2009; Henry and Piperno 2008; Henry *et al.* 2009, 2011a; Reinhart *et al.* 2001; Wesolowski *et al.* 2010). Debate remains, however, as to the reliability of such analysis in distinguishing between degraded raw starch granules and cooked, partially gelatinized granules (Collins and Copeland 2011; Henry *et al.* 2011b).

Plant-food microfossils, usually less than 50 µ in size, are typically recovered from tiny bits of residue found, often with the aid of a low-power microscope, in cracks and crevices and on use surfaces of chipped, ground, and battered stone tools as well as

wooden tools that came into *direct* contact with plant tissue. Starch granules and other plant-food microfossils have also been recovered from earth-oven sediments in tropical settings and from tephra-rich soil (Haslam 2004; Horrocks *et al.* 2004; Therin *et al.* 1999). We are not aware of any studies, other than our own (Thoms *et al.* 2011), that have identified and tracked plant-food microfossils *indirectly* deposited on earth-oven heating-element rocks during and after baking (i.e., in the absence of direct plant-to-artifact contact).

Plant-Food Microfossil Taphonomy

The potential to extract reliable information from plant-food microfossils in ancient earth ovens rests in part on an adequate understanding of microfossil taphonomy. The initial phase of plant-food microfossil taphonomy is represented by the pathways that microfossils follow from their raw state to baked residue status. These pathways are archaeologically relevant to the study of earth ovens because of the potential for microfossils in baking residue to be deposited *indirectly* on the heating-element rocks, which is to say without direct plant-to-artifact contact.

Much of the literature on starch taphonomy concerns preservation issues in sediments, on artifacts, and during cooking (Barton and Matthews 2006; Haslam 2009a; Henry *et al.* 2009; Messner 2011; Messner and Schindler 2010; Therin 1998; Therin *et al.* 1999). Other studies address the biological function of starch granules, phytoliths, and calcium oxalate crystals in plants (e.g., Haslam 2004; Miller 1992; Monje and Baran 2002; Piperno 2006). There is also considerable literature about the consumption of these plant microfossils by microbial organisms in the soil (e.g., Bot and Benites 2005; Cromack *et al.* 1977; Haynes and Francis 1993; Martin 1945, 1946; Webster *et al.* 2008).

A few studies demonstrate that ancient plant-food starch granules and phytoliths can be recovered from FCR and fired clay nodules (e.g., Poverty Point objects) presumed to have functioned as heating elements in earth ovens or for stone boiling (e.g., Cummings 1994, 2006; Perry 2010; Simms *et al.* 2013). Much of what has been discussed pertains to stone boiling, but those discussions are relevant to the topic at hand, given that water is also a key component in earth-oven technology.

With vast numbers of plant-food microfossils involved in geophyte baking, it seems plausible that some of them would survive the process and that at least a few of those might be preserved adequately enough on FCR for identification. What seemingly argues to the contrary is the likelihood that starch and other microfossils would be combusted by temperatures that often exceed 500 °C, as is the case when rocks are heated red-hot to fire an earth oven (Gose 2000; Jackson 1998). Moreover, starch granules experimentally subjected to boiling or baking undergo gelatinization that ostensibly renders most of them unidentifiable; the longer they are cooked the more so (Babot 2003; Henry *et al.* 2009; Reichert 1913). Wheat-flour starch, which is well studied, is transformed through swelling, loss of birefringence, melting, loss of crystallinity, increase of viscosity of the suspension, and leaching of amylose from the granules (Primo-Martin *et al.* 2007). The crystalline structure in some of the granules, however, is recovered sufficiently during the process of retrogradation for taxonomic identification.

In general, the extent of gelatinization, and hence a significant aspect of taxonomic identification potential, is controlled by moisture content, temperature, and cooking

time. These attributes are sufficiently variable in most baking processes to allow for some identifiable starch granules to survive (Messner 2011, p. 49–50). For example, a study of wheat bread baked in tins concluded: “...that during baking ca. 40 % of the starch in the crust does not gelatinize due to a lack of water. The fraction that loses its crystallinity regains it by retrogradation but only after a long time. By comparison, the gelatinized starch in the crumb regains its crystallinity much faster. It is not clear if this is due to the lower water content in the crust as compared to the crumb, as this would affect the kinetics of recrystallization” (Primo-Martin *et al.* 2007, p. 226).

Archaeologists have shown that identifiable starch granules and raphides in arrow arum (*Peltandra virginica*) rhizomes survived after baking in actualistic earth ovens, one with and one without a rock heating element (Messner and Schindler 2010). In both cases, all of the moisture for gelatinization emanated from the food and packing materials, as water was not added to the ovens. Starch granules in rhizomes that were quickly heated in close proximity to hot rocks and baked for 3 h exhibited more severe breakdown than did those heated slowly and baked for 12 h by an overlying fire. Their findings indicated that “it is not solely the temperature involved in the cooking process but rather the various heat transfer mechanisms used and the micro-climatic conditions they create that affect starch grain integrity most severely” (Messner and Schindler 2010, p. 334).

In a poster for the Australian Archaeological Association’s 2003 Poster Gallery titled “Mumu: Residue analysis of ethnographic and archaeological cooking stones from Papua New Guinea,” Alison Crowther, Micheal Haslam, and Robin Torrence summarized results of microfossil analyses of cooking stones from experimental and archaeological earth ovens. A variety of residues was recovered from experimental cooking stones, including gelatinized starch granules. Nondiagnostic charred plant tissue was found on a sample of cooking stones recovered from an ancient earth oven; no starch granules were found on the archaeological samples. All of the microfossils were attributed to the wrapping material or fuel, rather than to the food. Lack of identifiable plant-food microfossils was consistent with the researchers’ expectation that diagnostic food-tissue residue would be rare because plant foods cooked in earth ovens generally do not come into direct contact with the cooking stones.

There are several pathways by which identifiable starch granules survive the baking processes. First, too little water in a given cell may not allow for gelatinization of all the starch therein (Şumnu *et al.* 1999). Second, the small size of a given granule may prevent it from gelatinizing (Eliasson and Karlsson 1983; Messner and Schindler 2010). Third, if a given portion of the geophyte was not heated sufficiently long, gelatinization may not occur (Lund 1984; Messner and Schindler 2010). Fourth, granules may be protected from gelatinization by fat or sugar coatings (Lin *et al.* 1997; Şumnu *et al.* 1999). Such protective coatings may be especially important in geophyte starch-granule preservation, given that sugars make up a significant component of many USOs, including those used in the present experiments (Yanovsky and Kingsbury 1938).

In spite of the pervasive roles of soil microorganisms in the consumption of starch granules and other microfossils, numerous archaeological studies have shown that some microfossils survive these and other degradation processes in identifiable forms (Messner 2011, p. 50–52). For example, taro starch granules and xylem (i.e., vascular tissue) were recovered from sediment samples in an earth oven with a rock heating

element at an archaeological site in New Zealand (Horrocks *et al.* 2004). To the extent that plant-food starch granules from baking processes accumulate in earth-oven sediments, which presumably were not in direct contact with the food, it seems possible that they would accumulate as well on cook-stones therein. Also of relevance to the present article are experimental studies that assessed the movement of starch granules in sediments under the influence of groundwater. They indicate that, in general, (1) smaller granules move farther and faster than larger ones, (2) downward movement prevails but lateral and upward movement occurs as well, and (3) the movement of these granules in sediments should parallel to that of pollen (Haslam 2009a; Therin 1998).

To summarize and set the stage for the following discussions, (1) water is a major constituent of most USOs; (2) in oven baking, water plays a key role in regulating starch gelatinization, which facilitates digestion; (3) water also plays a key role in hydrolysis, which renders many USOs with complex carbohydrates, including inulin, more nutritious; (4) water loss (i.e., evaporation and dripping) from USOs and vegetal packing material is substantial during earth-oven baking; (5) identifiable starch granules and other microfossils survive the baking process; and (6) groundwater is an important mechanism for the translocation of microfossils in sediment. Collectively, results of studies reviewed here suggest that identifiable starch granules and other microfossils that survive the baking process might be deposited and preserved on FCR that functioned as heating elements in earth ovens. Ascertaining how and why plant-food residue is generated and transmitted is the subject of our experiments. *Our two-part working hypothesis is that (1) microfossils in various states of preservation are released from baking USOs as they emit water and (2) vaporized and emanating liquid water are mechanisms for transporting and depositing microfossils as components of emitted baking residue.*

Procedures and Methods

To address our hypothesis about the survival of identifiable starch granules and other microfossils in baking residue, we conducted three sets of experiments that entailed baking wild geophyte USOs in conventional (i.e., kitchen) and laboratory ovens. Our primary objective was to determine whether the resulting baking residues deposited on the insides of the bowls and on microscope slides suspended therein contained identifiable microfossils. USOs were baked in ceramic and glass containers for a few minutes to 12 h at temperatures between 135 and 150 °C (ca. 275–300 °F).

The first set of conventional-oven experiments, herein termed “simple,” entailed wrapping a handful of raw USOs in cotton cloth and baking the food bundle in an open glass bowl to which water was added periodically to keep the wrapping cloth and food *wet* and thereby avoid burning during prolonged baking. In the second set of conventional oven experiments, herein termed “complex,” a similar quantity of raw USOs was packed between layers of green-leaf packing material in a closed glass or ceramic bowl. In this case, a lesser amount of water was added periodically to keep the contents sufficiently *moist*, as opposed to wet, and thereby prevent burning. The lab-oven experiments represent the third set and herein are termed “vapor.” They were designed to more explicitly assess our hypothesis about the role of water in mobilizing

microfossils within a given USO and of water vapor in transporting and depositing them. Baked USOs and the residues deposited inside the various containers were sampled and processed to ascertain the presence and the nature of baked microfossils.

Case Study of Geophytes

Geophyte USOs store energy as various forms of carbohydrates, including (1) soluble sugar, primarily sucrose, a simple carbohydrate; (2) starch, a complex and major plant-storage carbohydrate; (3) glucomanna, a poorly understood nonstructural carbohydrate; and (4) fructan, especially inulin and inulin-like forms, another complex and major plant-storage carbohydrate (Miller 1992; Smith et al. 2001). Some USO's contain primarily starch, others primarily inulin-like fructan, and still other species store both starch and fructan or other complex carbohydrates (Ranwala and Miller 2008; Smith et al. 2001). Different kinds of carbohydrates require different cooking times and methods, which likely account for much of the diversity in earth-oven cookery. There are, however, patterns therein. Other things being equal, inulin-rich plant foods require longer cooking time to maximize caloric return than do starch-rich plant foods (Wandsnider 1997). Consistent with this principal, ethnographic and archaeological data illustrate that inulin-rich geophytes were baked for 2 to 3 days in large earth ovens with rock heating elements far more routinely than were starch-rich species (Boyd et al. 2004; Thoms 1989, Thoms 2008b, Thoms 2009; Smith et al. 2001; Wandsnider 1997).

A preponderance of evidence derived from previous research informs us as to which of numerous edible geophytes were or should have been sufficiently abundant to have been important in the diets of the hunter-gatherers in south-central North America (Acuña 2006; Boyd et al. 2004; Dering 2008; Laurence et al. 2011; Thoms 2008a). From our ongoing analyses of fresh geophyte USOs from this region, we also know which species are starch-rich and which are inulin-rich. For the baking experiments reported here, we selected three starch-rich geophytes native to east-central Texas: (1) false garlic (*Nothoscordum bivalve*) bulbs from sandy soil in the Post Oak Savannah, (2) rain lily (*Cooperia drummondii*) bulbs from clayey soil on the Edwards Plateau and silty soil along the interface between the Blackland Prairie and Post Oak Savannah, and (3) winecup (*Callirhoe involucrata*) taproots from sandy soil in the Post Oak Savannah (Fig. 2). From a continental perspective, these regions of Texas are part of the broad savannah ecotone that separates the southeast woodlands, central plains, and southwest deserts.

Most ethnographic and ethnohistoric accounts attest to geophytes being dug during the nongrowing or minimal growing season when bulbs, corms, tubers, and roots tend to contain their maximum quantity of potentially digestible calories and nutrients (Al-Tardeh et al. 2006; Miller 1992; Smith et al. 2001; Thoms 1989). We dug geophytes for our experiments intermittently during the fall and winter, from September 2009 to January 2013. During the fall, rain lily, false garlic, and winecup typically retain distinctive green leaves and, in the case of false garlic and rain lily, flower a few days after rainfall.

Winecup taproots and false garlic bulbs were dug the same day they were baked in a conventional oven. Rain lily bulbs were dug several weeks earlier and frozen until the day they were baked. The amount of time between collection and freezing varied as much as 3 days, which probably resulted in differential moisture loss. Variation in post-

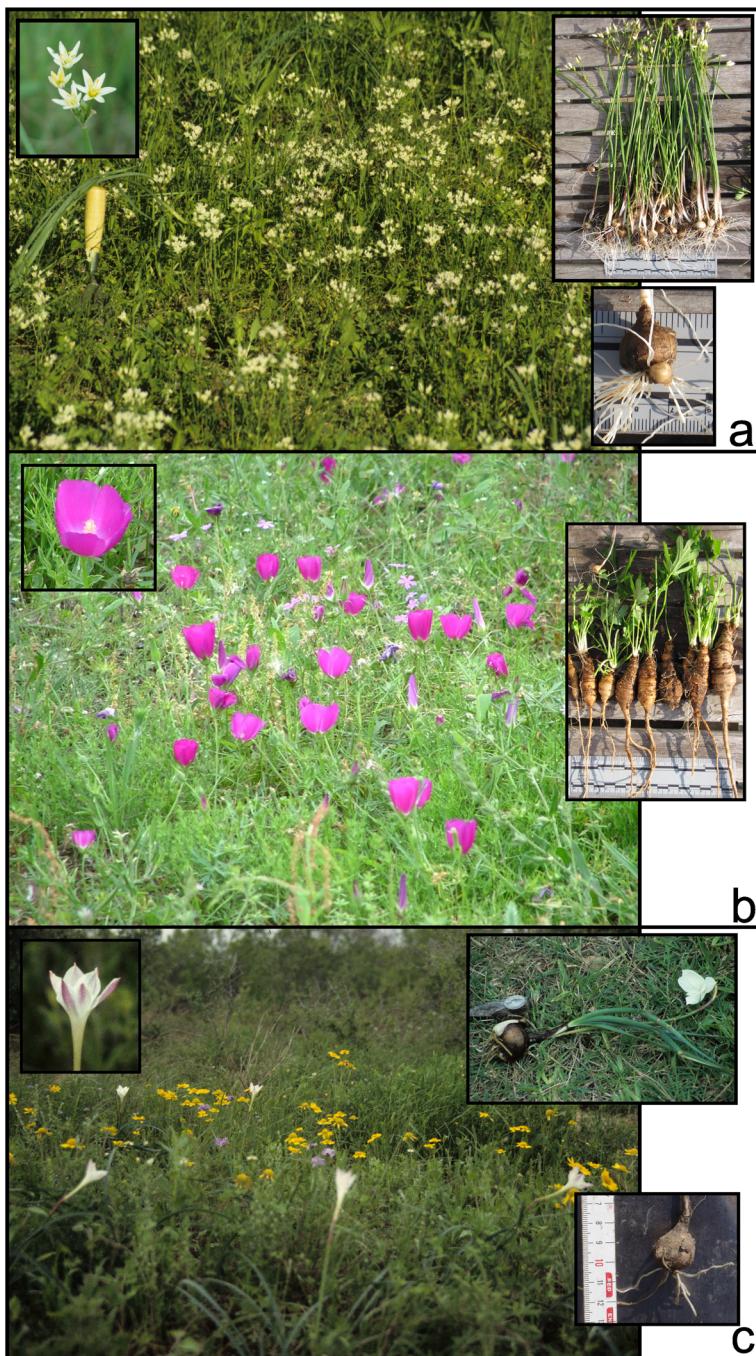


Fig. 2 Geophytes used in the present experiments and their USOs: **a** starch-rich false garlic (*Nothoscordum bivalve*) from sandy soil in the Post Oak Savannah, **b** starch-rich winecup (*Callirhoe involucrata*) taproots from sandy soil in the Post Oak Savannah, and **c** starch-rich rain lily (*Cooperia drummondii*) from clayey soil on the Edwards Plateau and silty soil along the interface between the Blackland Prairie and Post Oak Savannah (author's photographs)

collection treatment may affect the results of nutrient analyses, and potentially microfossil identification, because of microbe contamination or because nutrients in the nonedible portion can migrate to the edible portion during the freeze-thaw process (Kuhnlein 1986). We made multiple reference slides from fresh and frozen samples, and in all cases, the starch granules looked very similar. A study to evaluate results of different post-collection treatment techniques (i.e., no treatment, packing in dry ice, covering with 95 % ethanol, and air drying) revealed no significant differences relative to analyses of total nonstructural carbohydrates, including inulin-like fructan and starch. Although the effect of variation in the amount of intervening time between collection and analyses was not evaluated, that study's results suggested that specimens could be transported "considerable distances" without significant losses from enzyme activity or respiration (Fick and Nolte 1986, p. 43).

Some specimens analyzed for the present study were washed to remove sediments prior to freezing; others were washed after being frozen. In most cases, the outermost dried layers of the bulbs (i.e., tunic) were not removed before freezing. The extent to which variation in our collection times, post-collection techniques, and precooking preparations affected our analytical results is not clear, but it is unlikely to have significantly altered microfossil mobilization patterns.

Microfossil Extraction and Identification

Contamination Issues

In an article related to the present study, Laurence *et al.* (2011) reported finding starch granules and other microfossils in air samples taken on the Texas A&M University campus as well as from samples on an outside window seal of the lab where our USO and packing material samples were processed. Starch granules were recovered from analyst's hair samples and air samples within our lab (Laurence *et al.* 2011). To reduce these forms of contamination, analysts wore powder-free gloves and lab coats, either wore a hair cap or penned their hair, and they rinsed samples in filtered water and bleach or distilled water prior to processing.

All of the bowls used in the conventional oven experiments were washed in 5- μm filtered water immediately before use and kept covered between the times they were removed from the oven and processed for analysis. Cloth wrapping for the simple conventional oven experiments was cut from well-used clean kitchen towels recently washed in tap water. The electric kitchen oven in Thoms' home was used for the simple and complex baking experiments. It is possible, perhaps likely, that preexisting starch granules embedded in the oven's wall-residue were mobilized sufficiently to cause some contamination, particularly starch and microfossils from domestic species and especially for the open-bowl experiments. The chances of in-oven contamination probably were reduced substantially in the closed bowl experiments, which included oak and grass packing material. Insofar as nondomestic USO starch granules and other microfossils were the targets of our analyses, it is unlikely that preexisting residues significantly impacted the results, given that neither wild geophytes nor packing materials had been cooked previously in this oven.

Immediately prior to each round of vapor experiments, glass beakers and aluminum foil lids were washed in filtered water and bleach; fresh microscope slides were always

used. As discussed below, results of the vapor experiments in our new lab oven were similar to the conventional oven experiments in terms of the nature of wild plant starch granules and other microfossils found in the residues. We also baked control beakers and suspended slides (i.e., without USOs). Microfossils were not found on the control beakers or slides suspended therein. In summary, we recognize that preexisting microfossil residues may have been among those we found in some of our analyses and we contend, nonetheless, that consistencies in the nature of identified wild USO microfossils in the various experiments illustrate that our microfossil-mobilization findings are reliable and not the result of contamination.

Fresh USOs and Green Packing Material

Starch granules and raphides were extracted from raw and baked samples of false garlic and rain lily bulbs, winecup taproots, live oak leaves, acorns, little bluestem grass stems, and seeds following procedures reported by Field (2006). A bulb, taproot, leaf, or stem from each plant was bisected with a clean razor blade. For the bulbs and taproots, new toothpicks were used to scrape the inside of each storage organ. Two samples were taken from each storage organ. Material on the toothpicks was smeared onto microscope slides and allowed to dehydrate. One sample was mounted with water for immediate analysis and the other with Permount for curation purposes. We note, however, that some researchers have found that Permount mounting may not be conducive to long-term curation (anonymous reviewer, personal communication, 2014). For the live oak leaves and little bluestem grass stems, the interior of each sample was smeared directly onto microscope slides, allowed to dehydrate, and then mounted separately with water and Permount.

To obtain phytoliths, a small segment of each USO, grass stem and seed, or oak leaf and acorn was left in bleach until all of the organic tissues oxidized (Pearsall 2000, p. 339). Samples were then rinsed with distilled water, centrifuged, rinsed, and decanted three times to remove the bleach. Material remaining after decanting was placed on a microscope slide and allowed to dehydrate. The samples were mounted separately in water and Permount.

Baked USOs, Packing Material, and Residue

Recovery of microfossils from inside-baked USOs followed the same procedures described for fresh samples. Readily visible brown residues on the sides, bottom, and lids of the glass and ceramic bowls were recovered using a new toothpick to scrape a portion of the material and smear it onto a microscope slide. The residue on the slides was allowed to dehydrate prior to being mounted separately in water and in Permount. A different set of procedures was used to process the cotton cloths and green packing materials. A small piece of each cotton cloth or green packing material visibly stained with residue was removed and placed in a 50-ml test tube filled with distilled water. Test tubes were vortexed until the water turned a dark brown color. They were then centrifuged at 2,300 RPM to concentrate the material, and the supernate was decanted. A sample of the material was transferred from each test tube onto microscope slides using a pipette. The material was allowed to dehydrate, and the slides were mounted separately in water and Permount.

To test for microfossils deposited during the vapor experiment, residues adhering to the suspended slide and to the sides (but not the bottom) of the baking beakers were washed separately into a 50-ml test tube using filtered tap water. The fact that these residues were sparse and only faintly visible prompted us to use this wash-and-concentrate technique rather than the toothpick-smear method. Recovered material was centrifuged for 5 min at 2,300 RPM to concentrate the microfossils. The supernate was decanted and the remaining material was mounted on a slide. Baked taproots were sampled for microfossils by bisected using a sterile razorblade and scrapping the inner tissue with a toothpick. Material adhering to the toothpick was smeared on a microscope slide and mounted with water.

Simple, Conventional-Oven Baking: Wet Geophytes Wrapped in Cotton Cloth

For these experiments, we separately baked winecup taproots and false garlic bulbs on September 27 and October 17, 2009. The USOs were washed in tap water prior to baking, and some of the winecup taproots were partially peeled prior to washing (Fig. 3). Each species was wrapped in a moistened cotton cloth and baked in an *open* (i.e., uncovered) glass bowl. A small amount of filtered (5- μm screen) tap water was added periodically to maintain a consistently wet-to-moist cooking environment. Each time the water in the bowl evaporated, filtered water was poured over the cloth wrapping until 0.2–0.5 cm covered the bottom of the bowl and saturated the wrapping. As such, portions of the lowermost USOs in a given bowl were immersed in water much of the time.

Raw winecup taproots and false garlic bulbs are white to cream in color, very firm to hard in texture when squeezed between fingers, and slightly acrid in taste. These USOs were taste-tested after baking 8 h at 135 °C (ca. 275 °F) and found to be slightly sweet, with a distinctive molasses smell; they were brownish in color and less firm in texture. They were returned to the oven and baked at 150 °C (ca. 300 °F) for an additional 4 h. After baking a total of 12 h, the USOs were softer in texture, a bit sweeter, and browner in color. Judging from our previous experience baking geophytes, these were adequately cooked but it is likely that a few more hours of baking would have rendered them sweeter, browner, and softer. A brown caramelized residue (i.e., sweet tasting) covered parts of the wrapping cloths and bowl bottoms (Fig. 3).

Complex, Conventional-Oven Baking: Moist Geophytes Packed in Oak and Grass Leaves

What makes these experiments complex is the replacement of the cotton-cloth wrappings with green-leaf packing materials to better simulate earth-oven cookery. This added complexity was more realistic in that it introduced nonfood starch granules and other microfossils to the baking residue. For these experiments, we separately baked rain lily and false garlic bulbs and winecup taproots. Each set of geophyte USOs was baked between layers of live oak leaves (*Quercus virginiana*), with a few attached twigs and green acorns, and/or bluestem grass (*Schizachyrium scoparium*) that included leaves, stems, and a few seeds. We also used green leaves of winecup, false garlic, and rain lily as part of the packing material in their respective bowls. Winecup taproots and false garlic bulbs were dug, cleaned, and baked on the

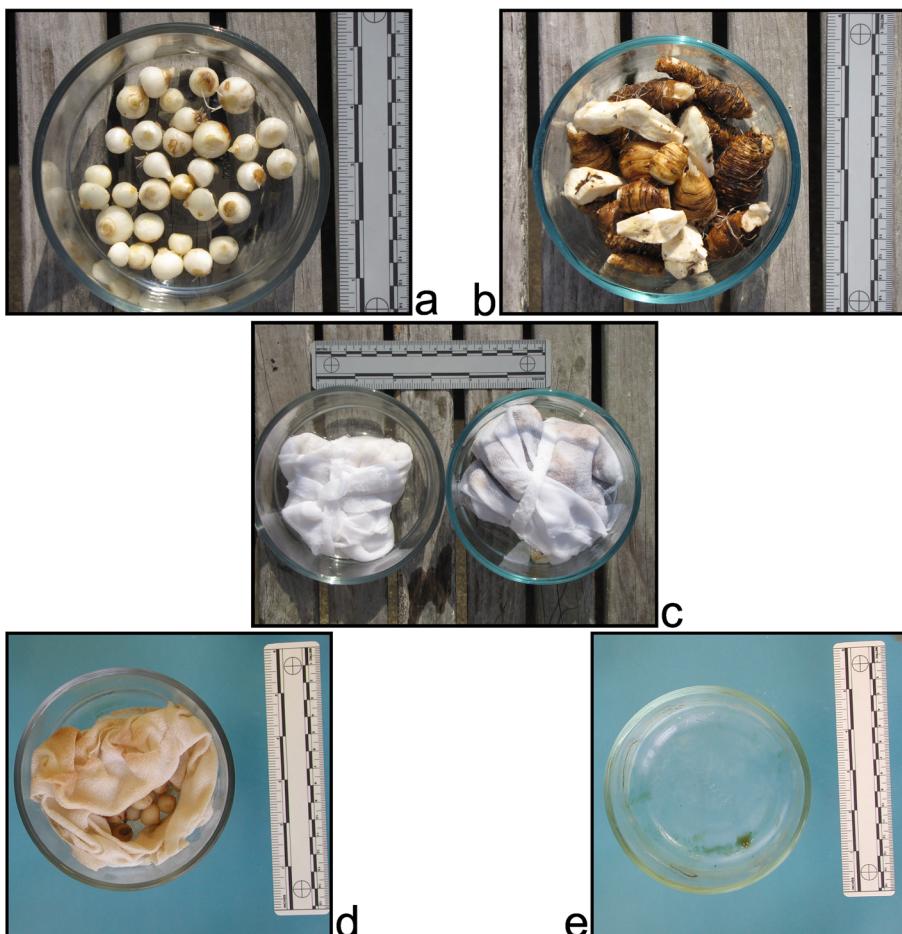


Fig. 3 Simple electric-oven baking experiment, false garlic: **a, b** fresh, raw bulbs in glass container used for baking; **c** bulbs wrapped in moist cotton cloth prior to baking **d** bulbs baked for 12 h wrapped in cotton cloth and soaked in water; and **e** cooking container with residue after 12 h of baking (author's photographs)

same day—October 31, 2009—along with rain lily bulbs that had been dug earlier in the fall and frozen.

Each species was baked in a *covered* glass or glazed ceramic bowl. The contents of the bowls were periodically moistened by an addition of small amounts of filtered tap water that partially coated the packing material and USOs but did not accumulate more than a thin lens of water on the bottom of the bowl (Fig. 4). These fresh, unfrozen, and thawed USOs and the leafy packing materials were baked for 12 h at 135 °C (ca. 275 °F). Most of the green packing material dried out and turned brownish in color but, in each case, some of it remained green and moist. The USOs were well-baked, still moist, within the range of a baked potato, and light brown in color. Bottoms, sides, and lids of the cooking containers were stained brown with slightly sticky, partially caramelized residue. Some of the packing material was stained with baking residue (Fig. 4). With the exception of rain lily, these baked geophytes were somewhat sweet and, overall, quite palatable. Raw rain lily is extremely acrid in taste (i.e., inedible) and



Fig. 4 Complex electric-oven baking, rain lily: **a** fresh, raw bulbs and packing material—grass and oak leaves with a few acorns—in glass container; and **b–d** bulbs and packing material after baking 24 h in a covered ceramic container (author's photographs)

considered to be toxic (Greathouse and Rigler 1941). Even the tiniest bite of baked rain lily bulb tasted acrid to the point of being inedible and perhaps still toxic, albeit with an initial hint of sweetness.

Vapor, Laboratory-Oven Baking: Bare Geophytes in Covered Beaker

These experiments are termed vapor because they were designed specifically to assess whether USO microfossils are mobilized and deposited *via* airborne water vapor during baking. Accordingly, a microscope slide was suspended by aluminum foil strips inside a covered glass beaker in a fashion that it was not in direct contact with either the geophytes being baked or the sides of the vessel. Water was not added to the beaker. We hypothesized, based on our understanding of the baking process, that vaporized water emanating from the USOs would carry microfossils into the air and condense on the suspended slide as well as on the sides and bottom of the beaker.

We conducted the vapor experiment multiple times with similar results reported below (Fig. 5). Each time, winecup taproots were dug and refrigerated for 1 to 7 days prior to baking in a lab oven. The leaves and long rootlets were removed, and the taproots were washed using filtered tap water to remove adhering sediment. The taproots were placed directly on the bottom of a clean (i.e., rinsed in distilled water) glass beaker, and a microscope slide was suspended above them to create a condensation platform for the water vapor. One beaker without taproots but with a suspended slide served as a control to test for the presence of airborne microfossils or other

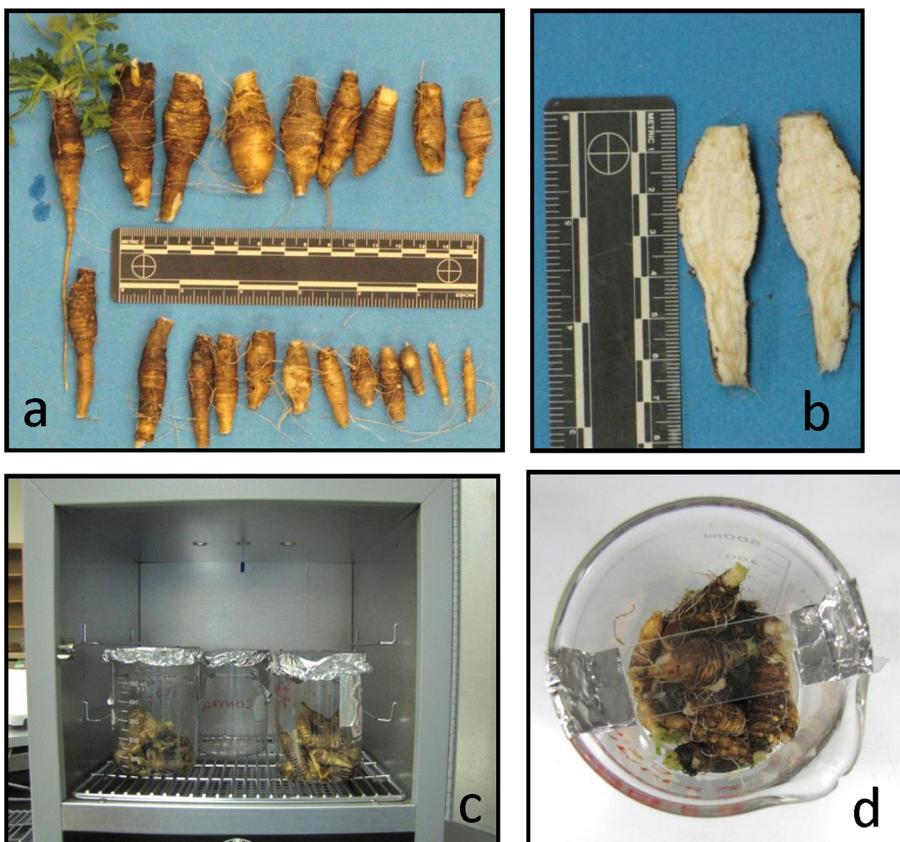


Fig. 5 Laboratory-oven baking, winecup: **a** fresh taproots, **b** bisected taproot, **c** lab oven with covered baking and control beakers, and **c** open beaker with taproots and suspended slide

contamination. Taproots of similar weights (ca. 18.5–65 g) were baked at temperatures ranging from ca. 160 to 220 °C (360–430 °F) for differing durations (0.25–2 h) to better understand the relationships between weight loss and baking time. Each beaker was covered with clean aluminum foil while baking. During the baking process, readily visible water droplets accumulated on the sides and lids of the beakers with USOs as well as on the suspended slides.

Analytical Results

Prepared microscope slides were observed under polarized, quarter-wavelength, and bright field microscopy using Nikon Optishot petrographic and Nikon Labophot microscopes. Slides mounted in Permount are curated at the Archaeological Ecology Laboratory, Department of Anthropology, Texas A&M University. All of the micrographs of plant microfossils were taken at $\times 400$ magnification. Electronic copies of micrographs used herein are also curated at the Archaeological Ecology Laboratory.

Apart from the starch granules, a wide variety of phytoliths, mostly nondiagnostic, were recovered from the USOs and packing material we analyzed. Figures 6, 7 and 8

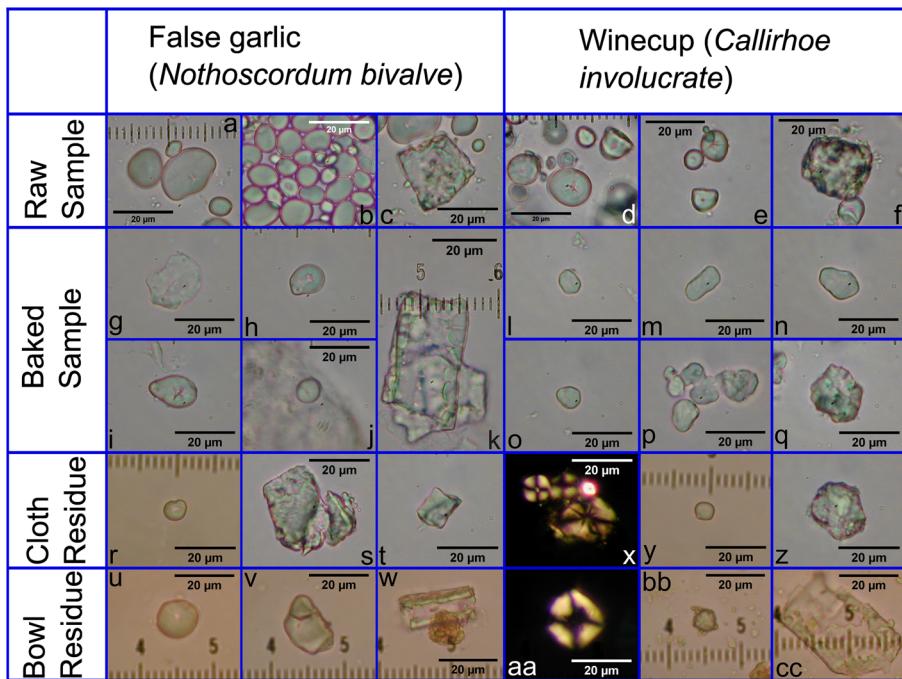


Fig. 6 Raw and baked geophyte microfossils from simple electric-oven experiment: recovered a, b, d, e, g–j, l–p, r, u, v, x, y, aa, bb starch granules and c, f, k, q, s, t, w, z, ccc phytoliths. Micrographs a–w, y, z, bb, cc are under bright field illumination, while x and aa are under cross-polarized light to show the intactness of the extinction cross (author's photographs)

illustrate a few examples merely to demonstrate their ubiquity. We did not study these phytoliths in sufficient detail to ascertain whether they may be diagnostic of a given family or genus.

Our residue analyses also revealed calcium oxalate crystals and tissue fragments. A detailed study of calcium oxalate crystals was not undertaken here, but some forms of these microfossils may well prove to be a valuable method of identifying plant foods baked in earth ovens. While plant tissues are not discussed in the present paper, their ubiquity and relatively good preservation in residue samples hint of their potential as plant-food identifiers. This is especially the case for inulin-rich plants with little or no starch, including camas, onions, and agave.

Microfossils from Raw USOs

Raw false garlic and rain lily bulbs as well as winecup taproots contained large quantities of starch granules and phytoliths (Figs. 6 and 7). Rain lily bulbs also contained raphides. Stems and seeds of little bluestem grass along with the leaves and acorns of live oak contained starch granules and phytoliths (Fig. 8). Starch granules from false garlic and rain lily, both Liliaceae (lily) family plants, exhibit similar characteristics and could not be readily differentiated. Following terminology in Reichert's (1913) starch-granule classification scheme, the assemblages from these lily species generally exhibit lenticular and oval-shaped (usually kidney-shaped) morphologies. Oval-shaped

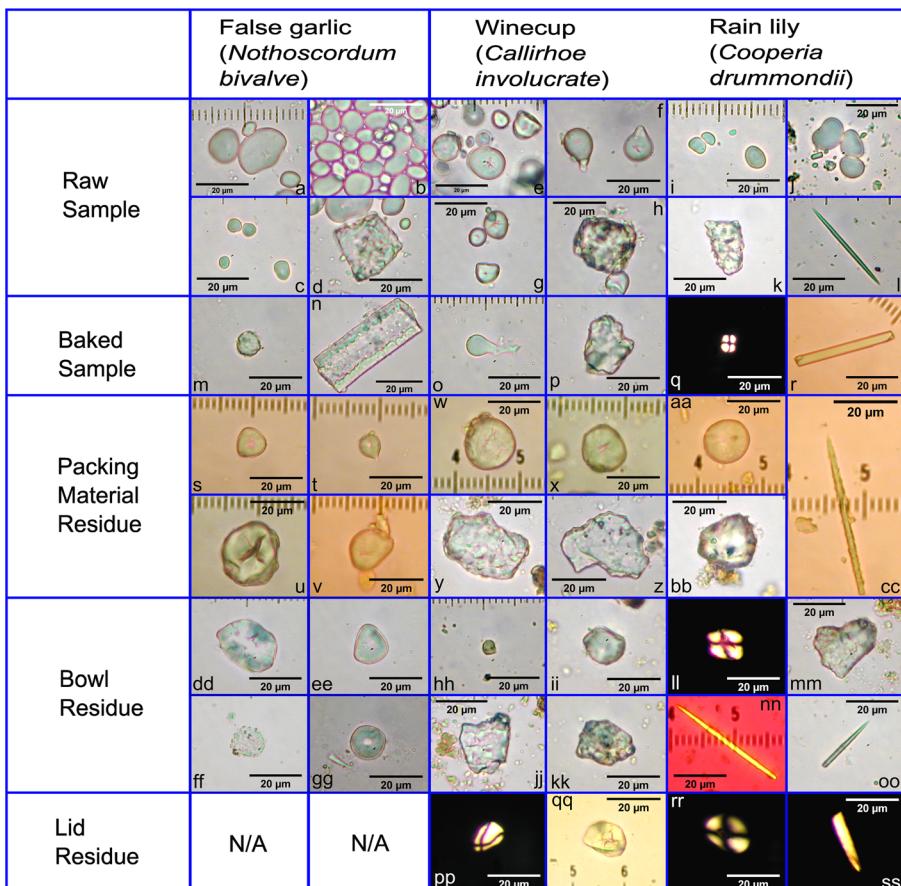


Fig. 7 Raw and baked geophyte microfossils from complex electric-oven experiment: recovered a–c, e–g, i, j, m, o, q, s–x, aa, dd–ii, ll, pp–rr starch granules, d, h, k, n, p, y, z, bb, jj–kk phytoliths, and l, r, cc, nn, oo, ss raphides. Micrographs a–p, r–kk, mm, oo, qq are under bright field illumination, q, ll, pp, rr, ss are under cross-polarized light, and nn is under one fourth wavelength polarized light. Calcium oxalate raphides are distinguished from phytoliths based on their color signature under polarized light (author's photographs)

granules usually are smaller than 5 µm in size; lenticular-shaped granules tend to be greater than 5 µm in size. Eccentric hilum, visible under bright field microscopy, are typical with y-shaped radial fissure. Lamellae, or concentric rings, are characteristic of all starch granules from these species. Most granules have a diagnostic rounded protrusion near the hilum which separates starch from these granules from those of the other investigated species.

Starch granules in raw winecup taproots have simple, compound, or semicomponent forms. Simple granules have visible eccentric hilum, single and y-shaped fissures, and are cone-shaped, although wedge-shaped granules also exist. Round granules with centric hilum are also present but not as common as eccentric granules. Compound and semicomponent granules are faceted on one or more surfaces. Visible lamellae are common in all types of granules.

Starch granules from fresh packing materials can be differentiated from those of raw USOs we analyzed (Fig. 8). Little bluestem grass granules have more or less centric

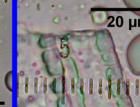
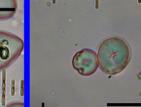
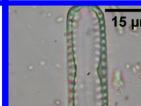
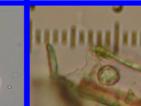
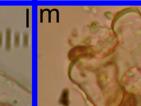
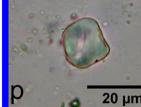
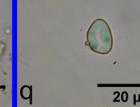
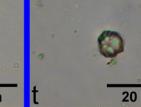
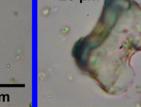
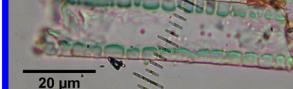
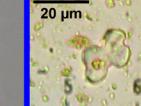
	Live oak (<i>Quercus virginiana</i>)		Little bluestem grass (<i>Schizachyrium scoparium</i>)	
Raw Sample	a  20 µm	b  20 µm	c  20 µm	d  20 µm
Baked Sample	N/A	N/A	N/A	N/A
Packing Material Residue	h  15 µm	i  20 µm	j  20 µm	m  20 µm
Bowl Residue	p  20 µm	q  20 µm	r  20 µm	s  20 µm
Lid Residue	 20 µm		y  20 µm	Microfossils not found

Fig. 8 Raw and baked packing-material microfossils from complex electric-oven experiment: recovered **a**, **d**–**f**, **l**, **p**, **q**, **t** starch granules and **b**, **c**, **g**, **h**–**k**, **m**–**o**, **u**, **r**–**y** phytoliths. Note the starch granule embedded inside a cell in **l**. All micrographs are under bright field illumination (author's photographs)

hila and are often spherical to slightly ovoid or faceted on all sides. Fissures radiating from the hilum are common, and concentric rings are sometimes visible. Compound and semicomponent granules also occur but are not as commonly as simple granules. Live oak starch granules are most commonly spindle-shaped with a transverse cleft. The hilum is visible in granules that do not have a transverse cleft. Lamellae are

common. Compound starch granules also occur in live oak but are not as common as spindle-shaped granules.

Microfossils from Simple, Conventional-Oven Baking Experiments

One day after being baked for 12 h, microfossils were recovered from USO samples and residues on the cloth packing material and from the sides and bottom of the glass and ceramic bowls (Fig. 6). Phytoliths were recovered from all sampled materials (Fig. 6c, f, k, q, s, t, w, z, cc). Most of the nongelatinized starch granules recovered from the samples were damaged to the point of being unidentifiable (Fig. 6g–j, l–p, u, v, aa, bb). Some, however, were identifiable, insofar as they were intact or slightly modified granules with most characteristics recognizable, thereby allowing for potential identification. Identifiable granules were recovered from cooking residue accumulated on the packing material and in the glass bowls for both false garlic and winecup. Identifiable, albeit nondiagnostic, starch granules were recovered only from one baked false garlic bulb (Fig. 6j). By “nondiagnostic,” we mean identifiable starch granules that could not be attributed to a specific family, genus, or species.

Microfossils from Complex Conventional-Oven Baking Experiment

USOs, packing materials, and residues from the bottom and sides of the containers used in these experiments were analyzed for microfossils 1 day after they were baked. The undersides of lids used to cover the rain lily and winecup USOs as well as the packing materials were also analyzed (Figs. 7 and 8). Baked winecup and rain lily USOs retained identifiable starch granules; phytoliths were present as well. Identifiable microfossils were not recovered from three tested false garlic bulbs. All of the residue samples, from the green packing material, sides, bottoms, and lids of the bowls, yielded starch granules and phytoliths.

Identifiable starch granules were recovered from the cooking residues of the containers used to bake false garlic and winecup. Note, however, that the compound granule in Fig. 7 hh could be from winecup, live oak, or little bluestem grass, making it an identifiable but nondiagnostic granule, given that compound starch granules occur in all three species. Raphides were recovered from residue in the bowl used to bake rain lily bulbs. Phytoliths, presumably from live oak, were found in residue on green packing material as well as in the bowls and on lids of vessels used to bake winecup and rain lily USOs (Fig. 8h–k, r, s, x). Live oak starch granules were recovered from the false garlic bowl residue (Fig. 8p, q). Phytoliths resembling those found in the raw little bluestem samples were recovered from all residue samples on the bottom of the bowls, on packing materials therein, and the underside of lids (Fig. 8m–o, u–w, y). A starch granule from little bluestem grass was also recovered from residue on the green packing material in the vessel used to bake false garlic USO's and in the residue on the bottom of the bowl used to bake rain lily USO's (Fig. 8l, t).

Microfossils from Vapor, Laboratory-Oven Baking Experiment

Small winecup taproots (ca. 18.5 g) lost 38–47 % of their raw weights after baking 30 min at 220 °C, moderate size taproots (ca. 64.5 g) lost 60–66 % of their raw weight

after baking 2 h at 180 °C, and large taproots (ca. 89 g) lost 11 and 32 % of their respective raw weights after baking at 160 °C for 30 and 60 min, respectively. Identifiable, but nondiagnostic, starch granules were recovered from suspended slides and beaker walls (Fig. 9). Nondiagnostic phytoliths and plant fibers were found as well. Most starch granules were substantially modified, but a few were identifiable (Fig. 9c and f). Insofar as microfossils were not recovered from the empty control beaker, it is likely that microfossils recovered from the beakers with USOs were from the winecup taproots, as opposed to some form of contamination, airborne, or otherwise.

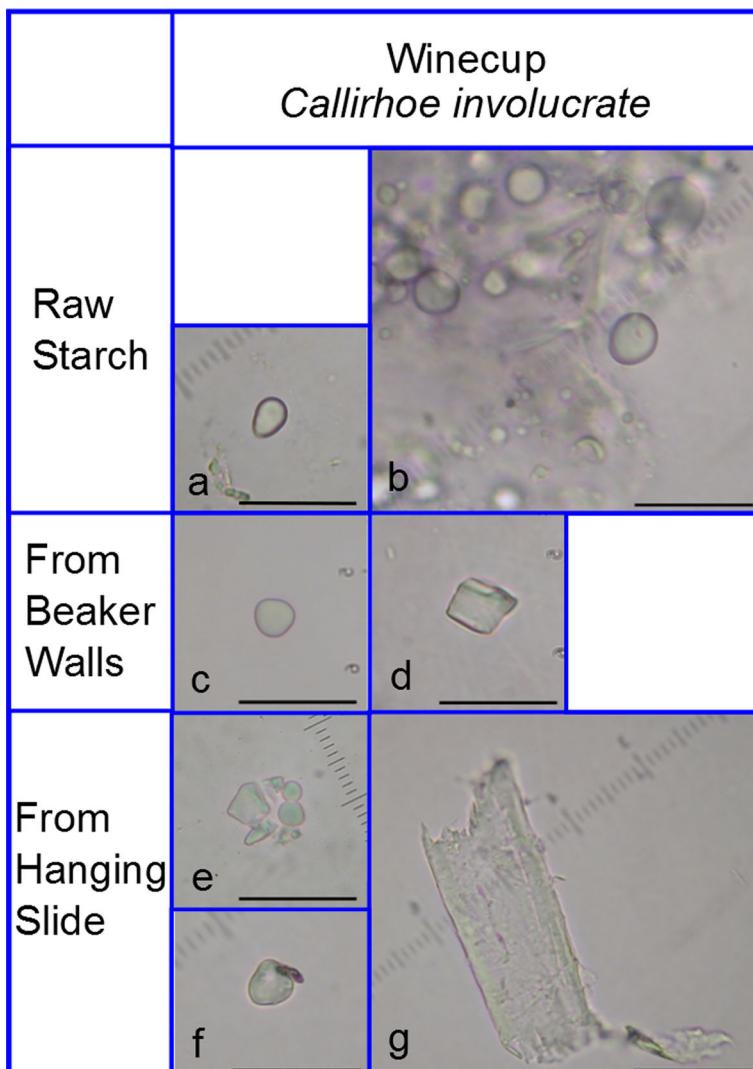


Fig. 9 Raw and baked winecup taproot microfossils from the lab-oven vapor experiments: **a–c, e, f** starch granules, **d** possible phytolith, and **g** plant fibers. All micrographs are under bright field illumination (author's photographs)

Summary of Results

Identifiable USO starch granules were recovered from the residues in bowls used to baked false garlic and winecup in both the simple and complex baking experiments. Identifiable rain lily starch granules were recovered from the complex experiment. Phytoliths were recovered in all residues and from baked USOs in both sets of conventional-oven experiments. Raphides were recovered from a baked rain lily bulb and from its bowl residue. Starch granules and phytoliths likely from the little bluestem grass and live oak packing material (leaves and/or acorns) were recovered in the packing material, bowl, and lid residues. Identifiable starch granules and nondiagnostic phytoliths from the winecup taproots were recovered from suspended slides and beaker sides in the vapor experiment.

Discussion and Interpretation

Insofar as identifiable starch granules are emitted from USOs and preserved in the caramelized baking residue on the inside of the baking vessels and on suspended slides, they should also be preserved as part baking residue on the inside of any given kitchen oven. To assess this contention, Laurence sampled and analyzed baking residue adhering to the inside surface of the oven in his home. A toothpick was used to scrape residue from the inside of the oven window. The residue was processed and analyzed in the same fashion as for the geophyte-baking experiments. Identifiable forms of domestic wheat (*Triticum* sp.) starch granules were recovered from the residue (Fig. 10). Although it was not evident when these starch granules were deposited on the oven window, wheat-flour products had not been cooked in the oven for at least 2 weeks prior to sampling. At a minimum, the recovered wheat starch granules underwent two baking events; the event corresponding with their deposition on the window and an event where domestic rice (*Oryza* sp.) and potato (*Solanum* sp.) products were baked in the oven 2 days before the residue was sampled.

The primary finding from our geophyte-baking experiments is that starch granules, phytoliths, calcium oxalate raphides, and plant tissue embedded in raw USOs are mobilized and emitted during short-term and prolonged baking. Each conventional-oven baking experiment ($n=5$) yielded some combination of identifiable plant-food microfossils on cloth wrappings or leafy packing material and in the bowl residue (Fig. 11). Results of these experiments support our hypothesis that upon baking, water within raw USOs plays a key role in mobilizing and depositing embedded microfossils.

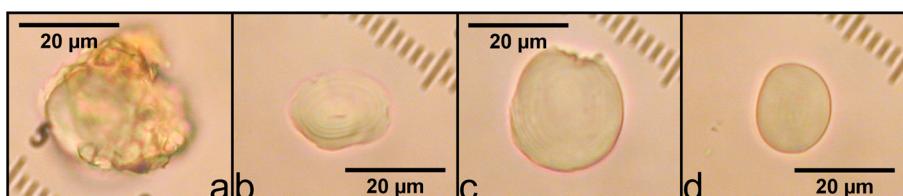


Fig. 10 Baked starch granules recovered from residue on the inside walls the electric oven at Laurence's home: **a** unidentifiable starch granule, **b** heavily modified wheat starch granule, **c** lightly modified but identifiable wheat starch granule, and **d** intact wheat starch granule (author's photographs)

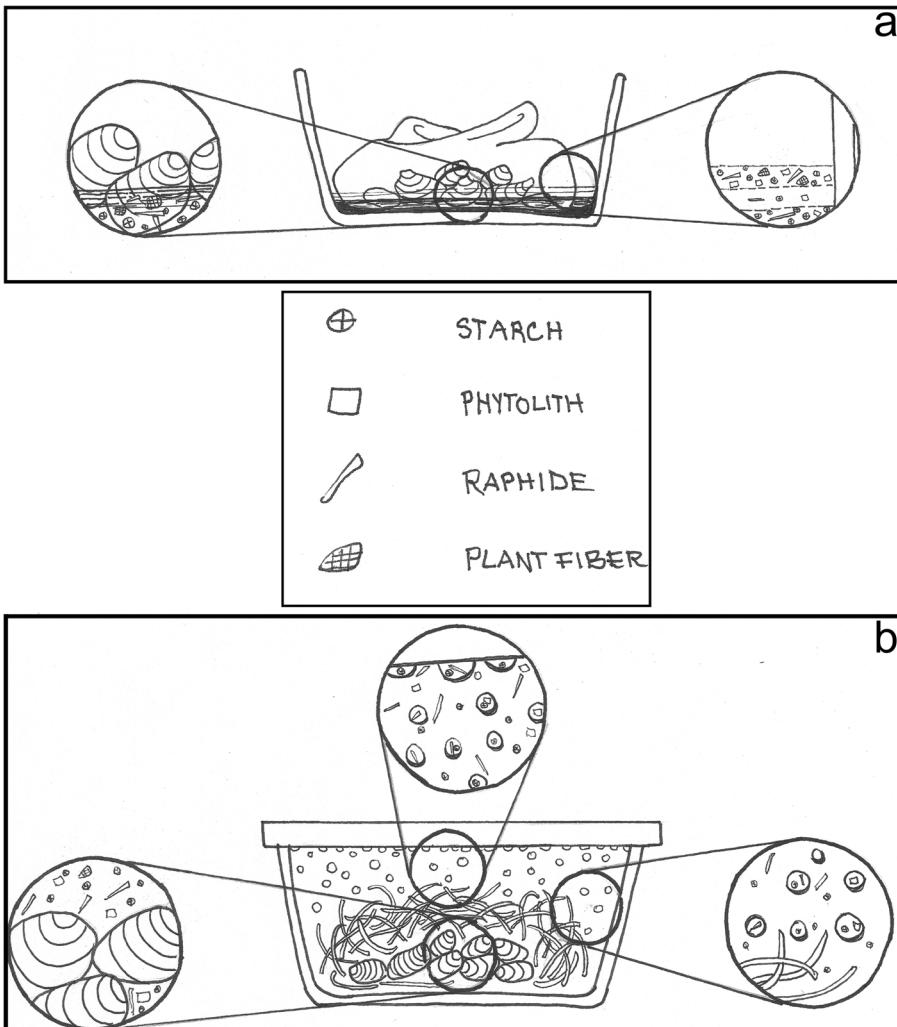


Fig. 11 Schematic illustration of initial taphonomy pathways: **a** release, distribution, and deposition of plant-food microfossils during long-term baking of saturated cloth-wrapped geophytes in an open glass container; and **b** release, distribution, and deposition of plant-food microfossils during long-term baking of geophytes in moistened green-plant packing material in a closed glass container with a ceramic lid (illustration by Marion Coe)

Our findings are also consistent with the recovery of taxonomically identifiable starch granules and raphides from geophytes baked in other experimental ovens and from those subjected to boiling (e.g., Henry *et al.* 2009; Messner and Schindler 2010). Accordingly, we conclude that it is indeed reasonable to expect to find plant-food microfossils in ancient earth ovens, given adequate preservation conditions.

Recovery of identifiable microfossils from residue deposited on the bottoms, sides, and lids of the baking containers and on suspended slides therein indicates that microfossils were mobilized in liquid and vapor forms of water. Our study's primary contention—water is a medium for microfossil mobilization—is significant, given that

water is a major component of most raw geophytes (Yanovsky and Kingsbury 1938). Much of that water, along with some of the nutrients, in a given USO is lost during prolonged baking (Bradbury *et al.* 1988; Konlande and Robson 1972; Kumar and Aalbersberg 2006; Thoms 1989, p. 158–159; Wandsnider 1997). We can now conclude that various microfossils also are lost during the baking process.

Our experiments suggest that during baking, heat-driven expansion of water within a USO results in microfossils being vented, *via* hot vapor and steam, from the confines of that USO. As per this working hypothesis, initial pathways for external dispersion of contained water (i.e., dehydration) may be the respiration-related passages naturally present within USOs (Al-Tardeh *et al.* 2008; Dhyani *et al.* 2009; Van der Toorn *et al.* 2000). As baking continues, USO temperature increases and water in the cells begins to vaporize. Internal air pressure should increase as well, thereby providing energy to expand respiration pathways and, importantly, rupture cell walls that encompass microfossils. Such hypothetical expansion cracks and openings would serve as mobilization pathways for escaping liquid and vapor forms of water, along with a diversity of inter- and intra-cell microfossils. These processes probably are analogous to what happens when a potato “whistles,” as today’s cooks sometime report hearing when this tuber is cooked (cf. internet search on “whistling potato”). A more generic analogy is witnessed by campfire gazers who see and hear small needle-shaped jets of blue fire as water vapor and hot air vent from burning green or wet wood.

As hypothesized here, USO microfossils are among the particles upon which water vapor droplets form (i.e., precipitate) during evaporation. With condensation of the water vapor on the packing material or on the sides, bottoms, and lids of the containers, and subsequent evaporation, microfossils remain as part of the baking residue. High-speed, high-resolution photography would be useful in further assessment of this hypothesis.

Archaeological Implications

Recovery of plant-food microfossils from baking residue on leafy packing material, the inside of containers, and on suspended slides suggests that substantial quantities of plant-food microfossils should be deposited on the voluminous packing material typically used when tens to hundreds of kilograms of USOs are baked in an earth oven. Our experimental results are consistent with our working hypothesis; they inform us that it is indeed reasonable to expect to find identifiable plant-food microfossils in the remains of ancient earth ovens. These results are sufficient to generate a follow-up hypothesis about post-baking translocation of plant microfossils during transition of an earth oven from its systemic context to the archaeological record: *With the passage of time, emitted plant-food microfossils, originally deposited on leafy packing material during baking, should be remobilized and moved down the profile by the percolation of rainwater or meltwater (i.e., soil illuviation).*

In this testable scenario, oven-mobilized, plant-food microfossils are remobilized along with other soil organic matter and cutans in general (Brewer 1960), *via* subsurface percolation, leaching, and evaporation. Subsequently, they are redeposited on underlying cooking stones and in the encasing sediment, along with residue from packing materials and other clay- and silt-size illuvium particles (e.g., soil carbonates,

organic matter, and other cutans). Some of the redeposited microfossils that come to rest on/around once-hot cooking stones should be protected from natural degradation, *via* soil microorganisms and enzymes, by the rocks (i.e., artifacts) themselves and perhaps by derived heavy minerals, including iron, and concentrations of clay-sized sediment, carbon, or calcium carbonate (cf. Haslam 2004, 2009b).

Assuming adequate survival rates, it should be possible to track plant-food microfossils in earth-oven cookery by following groundwater pathways through a given feature. Therin (1998) and Therin *et al.* (1999) recognized the possibility of microfossil translocation *via* groundwater but concluded that percolation's role in determining starch content in a given layer of soil was minor in comparison to microbial degradation of starch. Subsequent experimental work, however, indicated that downward, upward, and lateral movement of starch granules may be a significant taphonomic factor (Haslam 2009b). Micromorphological analysis (Goldberg and Macphail 2003) directed toward tracking microfossils within actualistic and archaeological intra-oven sediment profiles may further elucidate these hypothetical microfossil pathways.

Summary and Conclusions

Analysis of the cotton-cloth wrappings and bowl residue from the simple conventional-oven baking experiments demonstrated that intact/identifiable, gelatinized, and unidentifiable starch granules and other plant microfossils were emitted from geophyte USOs while partially immersed in liquid water. In this case, liquid water was a likely medium for the migration of microfossils through the cotton cloth and onto the bowl where they were incorporated into the brownish, partially caramelized, cooking residue. This finding supports the contention that stone-boiling rocks and clay nodules are also plant-food microfossil refuges (Cummings 2006; Perry 2010; Simms *et al.* 2013). Mobilization of microfossils in water vapor, as opposed to being immersed in liquid water, is indicated by the presence of identifiable starch granules and other microfossils found on suspended slides in the lab-oven experiment, on the underside of lids of cooking containers, and on the upper layer of leafy packing material in the conventional-oven experiments.

These results suggest that plant foods need not be in direct contact with cooking stones for embedded microfossils to be deposited or redeposited on heating-element rocks in earth ovens. Our findings also demonstrate that gelatinization of starch granules in wild-geophyte USOs sometimes remains incomplete after short-term and prolonged baking, a finding consistent with other studies (e.g., Henry *et al.* 2009; Messner and Schindler 2010). Said differently, a portion of emitted starch granules may remain sufficiently intact for identification within a given USO as well as in residue generated while baking for 12 h at temperatures of 135–150 °C (ca. 275–300 °F).

Recovery of little bluestem grass and live oak starch granules from our complex baking experiments indicates that packing-material microfossils are also emitted during prolonged baking. Here too, mobilization and deposition *via* liquid and vapor forms of water seems likely. Accordingly, nonfood microfossils should also be deposited on earth-oven heating elements and in the encompassing sediments. As such, the nature and distribution of plant microfossils in ancient earth ovens are likely to be analytically “noisy,” thereby complicating reliable extraction and identification of plant-food

microfossils. For example, leaves and stems of many edible plant foods may also be used as packing material, including those of berries, fruits, nuts, seeds, desert succulents (e.g., agave, prickly pear, yucca), and geophytes (e.g., *Balsamorhiza*, false garlic, mule ears, winecup). We conclude, nonetheless, that it is scientifically reasonable to expect to find USO microfossils in the remains of ancient earth ovens wherein those foods were baked.

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