The effects of cooking on avian eggshell microstructure

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Abstract

Although avian eggshell is a common component of the faunal assemblages at archeological sites, attempts to identify it taxonomically and use it to construct complex economic arguments have been limited. One method of identifying avian eggshell, using a scanning electron microscope (SEM) to examine characteristic microstructures, can provide more specific taxonomic identifications. This study sought to test whether cross-culturally common egg preparation methods were likely to damage eggshell in ways that would make it difficult to identify taxonomically under a SEM. We found that most food preparation practices caused minimal or no damage. Only cooking eggs in hot coals caused significant damage to eggshell microstructures, making it impossible to identify these eggshells taxonomically. With the exception of fire-cooked eggs, the lack of damage to eggshell microstructures meant that SEM analysis was sufficient to identify cooked eggshells taxonomically but insufficient to differentiate most cooking techniques.

Keywords

Avian eggshell, Eggs, Food preparation, Scanning electron microscopy, Zooarchaeology

1. Introduction

Avian eggshell is often recovered from archeological contexts when excavated sediments are wet-sieved through a fine mesh. Though avian eggshell may occur naturally in archeological deposits, most archeologically recovered eggshell probably results from subsistence practices.

While many projects do not attempt to assign avian eggshell fragments to taxonomic classifications, some projects use DNA analysis or examination of eggshell fragments under a scanning electron microscope (SEM) to identify avian eggshell more specifically.

Identification of avian eggshell using a SEM relies on being able to identify the particular morphology of the eggshell's mammillary cones, microscopic substructures whose formation varies by species. Successful identification requires that the eggshell be sufficiently intact to preserve undamaged mammillary cones. While potential sources of damage to mammillary cones have been identified (Beacham, 2006), the potential effect of cooking methods on mammillary cones has not been investigated. This study investigates the effects of cross-culturally common egg preparation methods on eggshell mammillary cones with the goals of understanding 1) whether and how egg preparation practices can affect mammillary cones, and 2) whether any damage to mammillary cones that occurs during egg preparation can be used to identify cooking methods.

Testing the possible effects of egg preparation methods on avian eggshell is one step in establishing criteria for identifying archeologically recovered avian eggshell to species and interpreting it in terms of subsistence practices. It is known that embryogenesis has an effect on the mammillary cone structure of avian eggshell (Beacham, 2007) and that avian eggshell is sensitive to erosional processes (Beacham, 2006). However, the possible effects of cooking practices on mammillary cone structure have not been investigated. If preparation methods do affect the microstructures of the eggshell, it is important to know the extent of these changes so that accurate species level identifications can be made. In addition, if it were possible to identify whether an egg had been cooked or, further, the type of cooking method used, this information would add a new dimension to the analysis of subsistence practices at archeological sites.

Avian eggshell is composed primarily of calcium carbonate stabilized with a small amount of protein matrix (Nys et al., 2004). As a carbonate, eggshell can be expected to react to acids and heat by releasing carbon dioxide and becoming more calcined and to react to carbon dioxide-saturated water by forming soluble calcium bicarbonate. All three of these reactions could potentially occur during preparation of eggs as food if whole eggs were baked or boiled. However, the occurrence of these reactions is dependent on both temperature and CO_2 pressure in the atmosphere. The calcination of calcium carbonate occurs only above temperatures of 550 °C at normal atmospheric pressure, suggesting that calcination of avian eggshell is unlikely to occur at most food preparation temperatures. While eggshell damage due to food preparation practices is chemically possible, the actual extent of such damage and its effect on the identification of the eggshells to species have not been investigated.

Based on the chemical composition of avian eggshell, we began this study with the hypothesis that the cooking times and temperatures involved in most cross-culturally observed egg preparation practices would not significantly affect the mammillary cone structures of avian eggshell and thus not prevent confident taxonomic identification. However, some low levels of change might occur that could help archeologists identify food preparation practices. We did not attempt to address the effects of burning avian eggshell as part of disposal practices, where much higher temperatures and more extended exposure to heat might occur.

2. Theory

The use of scanning electron microscopy to identify archeological eggshells has been employed only sporadically. Tyler (1970) attempted to identify avian eggshell fragments from Salamis using methods that included the examination of the eggs' mammillary cone layer. Keepax (1981) developed methodologies for taxonomically identifying eggshell fragments by examining the physical characteristics of the egg (i.e. thickness, shape, color, etc.) as well as its microstructure. Keepax (1981) noted that the microscopic structure of eggshell would be useful in identifying archeological eggshell fragments as the typical identifying characteristics of avian eggs - egg size, shape and color - would not be applicable. She outlined mammillae size, number, and height, as well as pore size, number, and shape as features that might be useful in the identification of eggshell fragments to species. Few additional studies attempted to taxonomically classify avian eggshell until the publication of Siddell's (1993) guidebook. Siddell's methodology expanded on Keepax (1981) by providing SEM images of the eggshell of numerous avian species along with the typical eggshell thickness, mammillae count, pore count, and surface descriptions for each species.

Since the publication of Siddell's manual, several studies have been conducted using scanning electron microscopy to identify avian eggshell (Beacham, 2006, Beacham, 2007, Boyer, 1999, Eastham and Iolo, 1997, Lamzik, 2013). Of these studies, most have focused on the use of the SEM to identify domestication (Beacham, 2006, Beacham, 2007), or to conduct comparisons between the avian bone assemblage of a specific site and its eggshell assemblage (Eastham and Iolo, 1997).

Archeological eggshell undergoes a number of destructive processes, including both taphonomic and human impacts. It has been shown that acids produced by decaying plant material can destroy calcareous eggshells and bone (Carpenter, 1982). Soil studies have shown that calcareous structures are more stable in low EH (reduction potential, or the tendency to acquire electrons), high pH soils with high levels of calcium carbonate (Retallack, 1984). In a study of both naturally eroded and experimentally treated eggshell, Clayburn et al. (2004) found that eggshell is expected to experience a greater chance of preservation in environments that are drier and alkaline. Though the mammillary structure was still evident in the naturally weathered eggshell, the detail in fresh eggshell was obliterated. In contrast, there was a deepening of craters in mammillae and dissolution of the margins of the mammillae in the experimentally treated eggshell. In addition, the dissolution of calcium carbonate from eggshell fragments occurred more rapidly the lower the pH and as temperature was increased in both the neutral and acidic solutions, there were increased losses in eggshell surface and thickness (Clayburn et al., 2004). While the taphonomic damages to avian eggshell have been studied (Carpenter, 1982, Clayburn et al., 2004), the effect of cooking processes on eggshell structure is not yet understood. Since it is known that taphonomic processes such as acidity and weathering can impact eggshell structure, it is possible that the concentrated heat exerted during some kinds of cooking or contact with slightly acidic or carbon dioxide-saturated water during boiling might also have an effect.

3. Methods

To study the effects of preparation methods on avian eggshell, we first identified likely methods of egg preparation through ethnographic and historical research. We then prepared eggs in each of the selected methods, choosing to use chicken eggs because they and the eggs of their ancestors the guinea fowl have been used worldwide as a food source throughout prehistory and history. We examined a sample of the shell of each prepared chicken egg using a scanning electron microscope. Finally, we compared our SEM images of the prepared chicken eggshells to existing SEM images of raw chicken eggshells to assess 1) whether damage had occurred, 2) the nature of any damage, 3) whether the damage would prevent successful identification to species, and 4) whether the damage was characteristic to specific preparation methods.

3.1. Selecting preparation methods

We selected our preparation methods through a combination of ethnographic, archeological, and historical research. Researching methods of egg preparation was not intended to provide an exhaustive list of all known methods but instead to provide an idea of preparation methods commonly used cross-culturally. We considered preparation methods that recurred more than three times in our research to be likely processes that may have affected archeologically recovered eggshells and therefore good candidates for investigation.

3.1.1. Historic and archeological uses of eggs

Due to the prolific nature of domestic hen laying, chicken eggs are an important source of food in the modern world (Serjeantson, 2009). Wild and farmed eggs were also ubiquitous in past diets. In the New World, Darwin discovered that people were eating rhea eggs when he first visited South America (Darwin, 1897). High frequencies of burned and unburned *Rheidae* spp. eggshell confirm the importance of this resource in West Central Argentina throughout the Holocene (Giardina et al., 2013, Medina et al., 2011). Moa eggs were important in past diets in New Zealand (Oskam et al., 2011). Seabirds have provided an important source of wild bird eggs in North America; for instance, the Tlingit of the Pacific Northwest Coast traveled to offshore islands to obtain seabird eggs (Oberg, 1980) and the Nunamiut of Alaska used the eggs of the arctic tern (Nelson, 1969).

Seabirds also provided a reliable source of food in the Old World. Arctic tern eggs were considered a delicacy in the Faroe Islands (Williamson, 1949) and eggs from a variety of wild birds were taken up until the last century in Norway (Bratrein, 2005). Both burned and unburned eggshell was found in an occupation layer dating to 16,000 BP at Nunamira Cave, Tasmania (Cosgrove, 1995). There is also a great deal of historical and archeological evidence for the use of domestic birds for egg laying. The omnipresence of chicken eggshell at Mons Claudianus in Egypt indicates that efficient egg production techniques were practiced at this Roman-period quarry site (Hamilton-Dyer, 1997). Additionally, the Roman author Columella (1941) provides detailed instructions for the raising of birds for egg production. Domestic chicken eggs were consumed in large quantities in Medieval Europe (Harvey, 1993), and in the Middle Ages, egg production reached almost industrial standards, with some Medieval authors citing yields of up to 122 or even 180 eggs per hen per year (Stone, 2006).

3.1.2. Traditional egg preparation methods

We searched the ethnographic and archeological eHRAF databases for the terms “bird eggs” and “cooking” under the category of “food preparation.” The search returned 41 individual relevant responses in the ethnographic database, and 0 relevant responses in the archeological database.

The most commonly referenced method of cooking bird eggs was boiling, with five references. The Teda of Chad (Le Coeur and Schütze, 1950), the Lapps of Finland (Itkonen and Minn, 1948), and the Badagas of India (Hockings, 1980), the Koryak of Komchatka (Jochelson, 1908), and the Paiute of California (Kelly, 1934) all eat boiled eggs. Additionally, the Roman cookbook attributed to Apicius contains both a recipe for hard-boiled eggs as well as a recipe for a sauce for soft-boiled eggs. Although these ethnographic and historical sources mention that ‘hard-boiled’ or ‘boiled’ eggs were eaten, none of them were explicit about actual cooking methods, such as cooking time.

Baking eggs was the second most commonly referenced method of cooking bird eggs, with three references. The Selk'Nam of Argentina and Chile open a small hole in the shell and leave the eggs in the ashes until the eggs are “cooked as hard as stone (Gusinde, 1931).” Likewise, the Paiute of the Great Basin both bake eggs underneath ashes or boil them (Kelly, 1934). The

Araucanians of Chile and Argentina use a combination of scrambling and baking to cook eggs (Hilger, 1957). This is done by first peeling one end of the shell off, stirring the yolk and white inside the shell with a stick, and then adding salt to taste. The egg is set ‘close to the edge of the fire’ and in order to insure that the egg is thoroughly cooked the contents are either stirred with a stick or the egg itself is repeatedly turned (Hilger, 1957).

It is also common for eggs to have been fried or made into omelets as in the Badagas culture of India (Hockings, 1980). The Lapps of Finland bake egg cakes with a mixture of flour, water, eggs and fat (Itkonen and Minn, 1948). Additionally, the Lapps would mix eggs with milk and cook them (Itkonen and Minn, 1948), presumably in a method similar to scrambling (Table 1).

Table 1. Common egg preparation techniques with cultural references.

Egg preparation type		Culture	Country or region	Reference
Eggshell exposed to heat	Boiled	Teda	Chad	Le Coeur and Schütze (1950)
		Lapps	Finland	Itkonen and Minn (1948)
		Badagas	India	Hockings (1980)
		Koryak	Kamchatka	Jochelson (1908)
		Paiute	California, USA	Kelly (1934)
	Baked	Selk'Nam	Argentina and Chile	Gusinde (1931)
		Paiute	California, USA	Kelly (1934)
		Araucanians	Chile and Argentina	Hilger (1957)
Eggshell not exposed to heat	Fried	Badagas	India	Hockings (1980)
	Egg cakes	Lapps	Finland	Itkonen and Minn (1948)

Egg preparation type	Culture	Country or region	Reference
“Scrambled”	Lapps	Finland	Itkonen and Minn (1948)

As shown in these ethnographic sources, the cooking of eggs has been broadly documented. While there are a number of different methods used, there are three common ways in which we would expect the eggshell itself to be altered: 1) it would be fragmented, and not cooked, as it would be if the eggs were used for baking or to make omelets, 2) it would be exposed to boiling water, as in hard- or soft-boiling, and 3) the eggshell would be exposed to the high temperatures of a fire as the contents are baked in shell.

3.1.3. Obtaining eggs for experimental preparation

To ensure that damage to the avian microstructure would be analogous to archeological avian eggshell samples, we selected eggs that came from chickens that were not industrially farmed. In the authors' experience, the bones of industrially farmed chickens are highly porous and do not ossify fully, making them poor proxies for the bones of pre-industrial or wild birds. To avoid similar discrepancies that might be true of industrially produced eggs, our experiment used organic eggs from hormone-free chickens raised in an environment we thought would reflect that of chickens raised by pre- and non-industrial societies. We purchased the eggs at a farmers' market in Buffalo, NY. We selected eggs laid by coop-raised chickens that were never caged. In summer, the chickens exclusively foraged naturally for food over a range of over 100 acres. In winter, when foraging was not possible, they were fed only organic feed.

3.2. Preparation and analysis

We chose to examine boiling, oven baking, and fire baking due to their prevalence in global ethnographic and historical contexts. We also examined an unprepared eggshell as a control specimen. It is important to note that cooked eggs may be represented in the archeological record by eggshell that was not cooked. This would be the case if raw eggs were used as an ingredient in cooking or baking or to make omelets.

3.2.1. Egg preparation methods

We prepared the organic, free-range eggs in four different ways: boiling for three minutes, boiling for twelve minutes, baking in a closed oven at 177 °C (350 °F) for 20 min, and baking in an open fire for 10, 15 and 20 min. The boiled eggs and the oven-baked eggs were prepared using a conventional electric oven. The fire-baked eggs were prepared by placing the eggs on the hot coals of an open wood fire when the coals were around 520 °C. When the 10, 15, and 20 min fire-baked eggs were removed from the coals, the coal temperatures were 220°, 250–270°, and 196° respectively. Two eggs were prepared for the oven-baked, boiled 3 min, and boiled 12 min methods, while one egg was prepared for each of the fire cooking times.

We examined two fragments of the oven baked, boiled 3 min and boiled 12 min eggs as well as two fragments of unprepared eggshell. We selected three fragments from each of the fire-cooked eggshells; two of the fragments were visibly charred, while one fragment did not show any visible signs of burning. The scope of our study was limited by available funding, but further expansion of this experiment by testing more samples from each preparation method to control for variation would be beneficial.

3.2.2. Preparation of eggshell for SEM analysis

Before examining an eggshell's mammillary cones under a SEM, the thin membrane covering the inner surface of the egg, the *membrane putaminis*, must be removed. We randomly selected two-three fragments (< 5 mm^2) from each prepared eggshell for examination and placed the selected fragments in 100% bleach for 20 min to remove the *membrane putaminis*, following the methodology given by Siddell (1993). We then removed the eggshells from the bleach, rinsed them with water, and placed them on paper towels to dry.

3.2.3. Microscopic analysis

We examined each eggshell under a regular light microscope and counted the number of pores/mm^2, and the thickness in mm, using the standard measurements described by Siddell (1993). These methods had previously been described, in part, by Keepax (1981), though they were further refined in Siddell's methodology. For a measurement of shell thickness, we used an eyepiece graticule in a light microscope that was calibrated to mm. We took several readings from each eggshell fragment to ensure accuracy. It is also possible to use digital calipers (Siddell, 1993) or a small bench micrometer with a digital readout (Eastham and Iolo, 1997) to measure eggshell thickness. The number of pores/mm^2 on the external surface of the eggshell was also obtained by using an eyepiece graticule with a grid. We took three counts from within the same mm^2 of each fragment and calculated the average. We compared our measurements against Siddell's numbers for chicken eggshell thickness and pore count to ensure that they fell within the standard ranges given by Siddell for chicken eggshells; all fell within an acceptable range of variation (Table 2).

Table 2. Measurements for our cooked eggshell along with Siddell's standard measurements for chicken eggshell. Standard chicken pores/mm^2 is the mean for a sample size of 20 chickens (Siddell, 1993).

	Pores/mm^2	Thickness (in mm)
Chicken (Siddell, 1993)	2.8	0.325–0.35
Raw	3	0.325
Boiled 3 min sample 1	2	0.350
Boiled 3 min sample 2	3	0.40
Boiled 12 min sample 1	3	0.325
Boiled 12 min sample 2	4	0.350
Baked 20 min sample 1	3	0.350
Baked 20 min sample 2	3	0.30
Fire cooked 10 min sample 1	1	0.325
Fire cooked 10 min sample 2	3	0.350
Fire cooked 10 min sample 3	3	0.320
Fire cooked 15 min sample 1	5	0.350
Fire cooked 15 min sample 2	3	0.350
Fire cooked 15 min sample 3	3	0.325
Fire cooked 20 min sample 1	3	0.40
Fire cooked 20 min sample 2	2	0.320
Fire cooked 20 min sample 3	3	0.325

3.2.4. SEM analysis

We mounted each eggshell fragment mammillary cone side up on an aluminum stub using a carbon conducting double-sided sticker. We placed the stubs in a carbon sputter coater, which coated the samples in a thin layer of carbon. After each fragment was coated, we used a Hitachi S4000 field emission scanning electron microscope to examine and capture images of each fragment. We took image captures at 200 × magnification.

We examined each image and looked at several factors: mammillae definition, mammillae shape, mammillae spacing, and the depth of the fissures between the cones. The mammillae definition was classified as well, fair, or poor. Mammillae shape was classified as either regular or irregular. The spacing of the mammillary cones was classified as regular, fairly regular, slightly irregular, or irregular. The fissure depth was classified as shallow, moderate, or deep; in some instances, the fissure depth was given as a range. These categories were largely based on those used in Siddell's (1993) guide (Table 3).

Table 3. Qualitative descriptors used for SEM images of eggshell (Siddell, 1993).

	Mammillae definition	Mammillae shape	Spacing of cones	Fissure depth
Standard chicken (Siddell, 1993)	Well	Fairly regular	Irregular	Moderate
Raw	Well	Irregular	Irregular	Shallow-moderate
Boiled 3 min (1)	Well	Irregular	Slightly irregular	Moderate-deep
Boiled 3 min (2)	Well	Regular	Slightly irregular	Shallow-moderate
Boiled 12 min (1)	Well	Irregular	Irregular	Moderate
Boiled 12 min (2)	Fair	Irregular	Irregular	Moderate-deep
Baked (1)	Fair	Irregular	Irregular	Shallow-moderate
Baked (2)	Well	Irregular	Irregular	Moderate
Fire cook 10 min (1)	Well	Irregular	Irregular	Moderate
Fire cook 10 min (2)	Well	Irregular	Slightly irregular	Moderate
Fire cook 10 min (3)	Fair	Irregular	Slightly irregular	Moderate
Fire cook 15 min (1)	Fair	Irregular	Irregular	Shallow-moderate

	Mammillae definition	Mammillae shape	Spacing of cones	Fissure depth
Fire cooked 15 min sample 2	Fair	Irregular	Irregular	Shallow
Fire cooked 15 min sample 3	N/A	N/A	N/A	N/A
Fire cooked 20 min sample 1	Well	Irregular	Irregular	Shallow-moderate
Fire cooked 20 min sample 2	N/A	N/A	N/A	N/A
Fire cooked 20 min sample 3	N/A	N/A	N/A	N/A

In order to make these assignments, each researcher independently made their assessment of each criterion and then discussed their assessment with the other. Analysis of all our variables placed these eggshells within the variation described by Siddell with the exception of several of our fire-cooked eggshell samples.

4. Results

There were no significant differences among the boiled 3 min, boiled 12 min, and baked eggshells when they were viewed under the SEM. The shell fragments from the eggs that were raw, oven-baked, boiled 3 min, and boiled 12 min were all within the thickness range and pore count described by Siddell (1993) for chicken eggs. In addition, our analyses of the visible features of the egg (mammillae definition, mammillae shape, mammillae spacing, and fissure depth) were all within the acceptable variation we would expect for chicken eggs. All samples had well-defined mammillae that were irregularly sized and spaced. They had moderate fissure depth (Fig. 1).

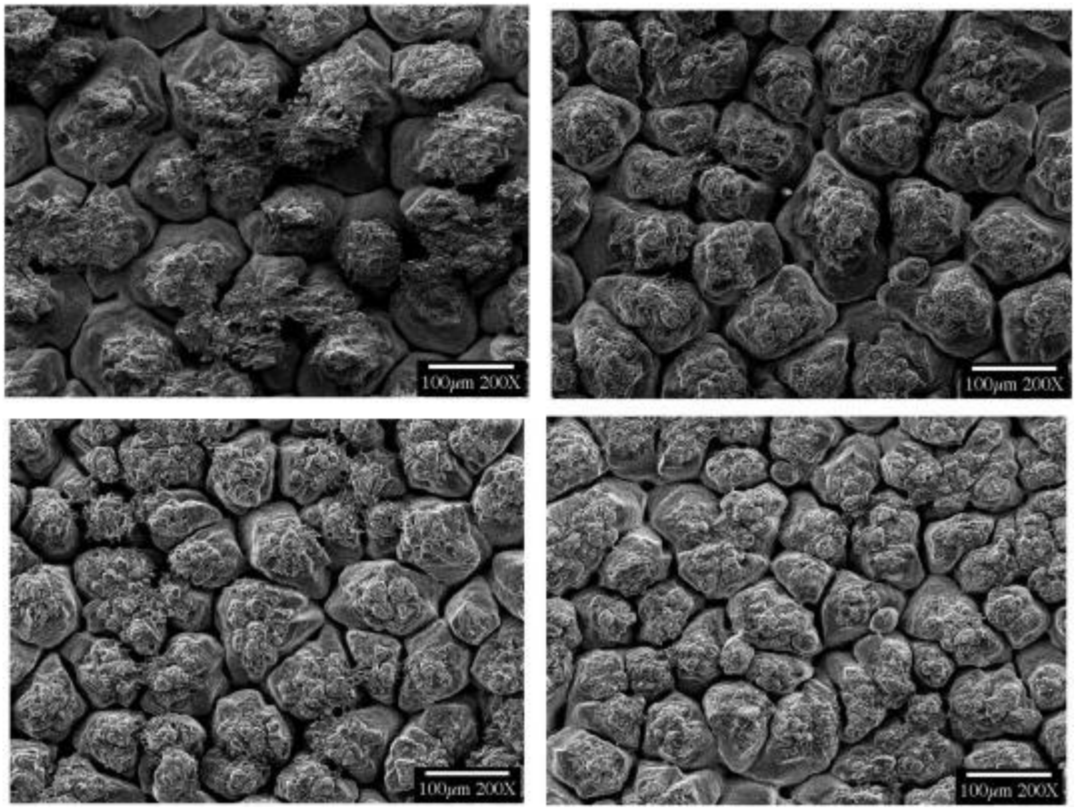

Fig. 1. SEM Images of (from top left to bottom right) raw egg, boiled egg 3 min, boiled egg 12 min, and baked egg 20 min.

Though there were no significant differences among the raw, boiled, and baked eggshell, there were varying degrees of damage present on the fire-cooked eggshell. Some of the fire-cooked eggshell fell within the same range of variation shown in the eggshell prepared by other means, though several of these fragments had small areas of damage. These damaged areas appeared as depressed spots on the mammillary cone layer, with little to no definition among the mammillary cones in this structure. Three of the fire-cooked eggshell fragments were unable to be identified as chicken due to the complete obliteration of the mammillary cone structure (Fig. 2).

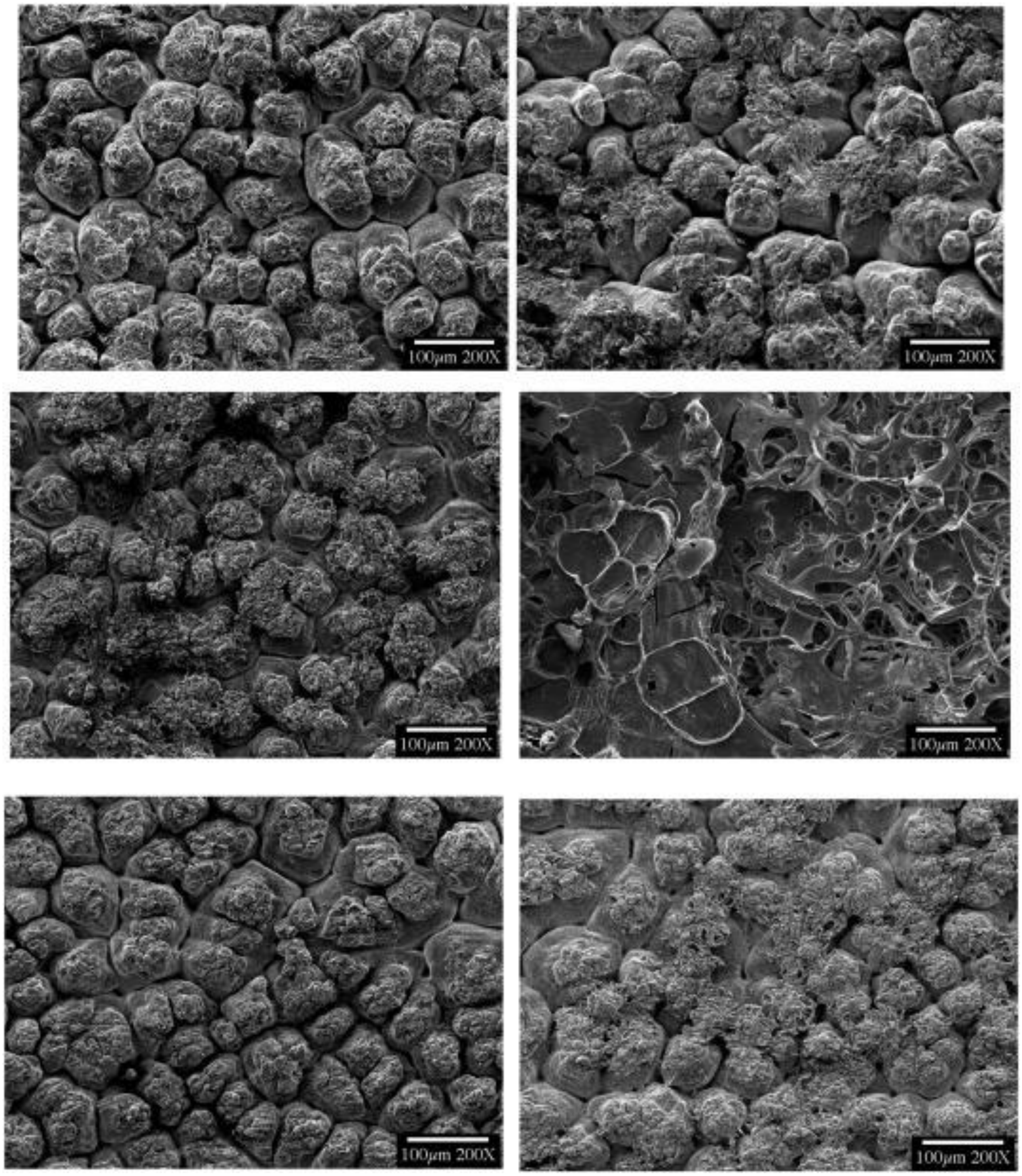

Fig. 2. SEM images of from top to bottom: Fire cooked egg 10 min, fire cooked egg 15 min, and fire cooked egg 20 min. Non-charred fragments are presented on left, charred fragments on right.

Fire cooking appeared to cause delamination of the mammillary cone layer. Though we purposefully selected samples that appeared to be burned (blackened), in some cases the bleach solution caused some of the blackness to come off, leaving behind a white-brown coloring on the eggshell. It is likely that these samples simply had some residual soot from the coals present. These samples with residual soot, but not actual charring, did not have the extreme delamination that was present on the more charred fragments of eggshell. However, the beginnings of delamination can be seen in some of these samples, as in the images of the fire cooked 10 min and fire cooked 20 min eggs above. Additionally, some of the fragments that did not have visible charring showed the beginnings of delamination (see fire cooked egg 15 min above; Fig. 3).

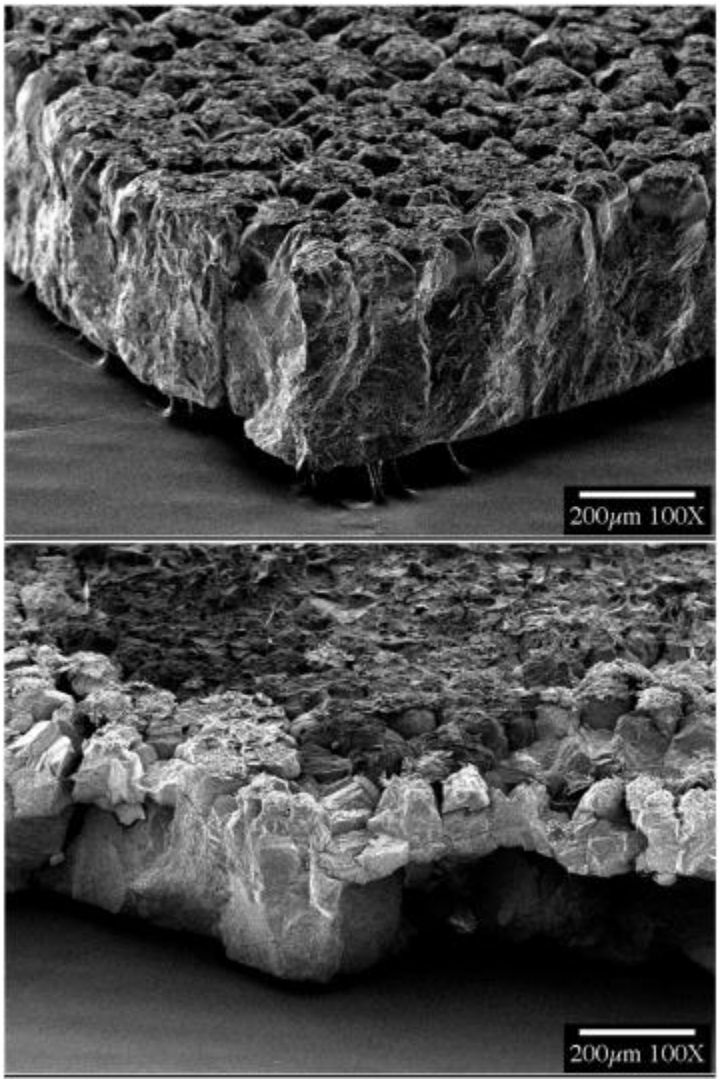

Fig. 3. SEM image showing side view of raw egg (top), and Fire cooked egg 20 min (bottom). Note the delamination of the mammillary cone layer in the bottom image.

5. Discussion and conclusions

Based on our findings, there is little to no damage to the eggshell microstructure during most of the more common cooking methods. The fact that the majority of our cooked samples showed no damage to the mammillary cones and were identifiable as chicken eggs means that, in the absence of further destructive taphonomic processes, archeologically recovered cooked eggshell will be easily identifiable. Eggs that have been hard-boiled, soft-boiled, and oven-baked will be identifiable to species. This is promising, since many of the eggshells found at archeological sites are the result of subsistence practices, and many were probably cooked in the shell using one of these three methods. Our study was limited in funding and time, but it would be beneficial to expand this study using other commonly found eggs such as duck or goose in order to determine whether these results are common across species.

Our study also indicates that SEM examination is not a viable method to differentiate between most of the more common cooking techniques. Hard-boiling, soft-boiling and oven baking cannot be differentiated using a SEM.

The exception to these general observations is the fire-cooked eggshell. Fire cooking produced clear and diagnostic damage on some parts of the cooked eggshells, though fire cooking itself was not a perfect predictor of mammillary cone damage. This has some important implications. Firstly, fire-cooked eggs may still be identifiable to species using a SEM if less damaged fragments of eggshell are selected for examination. Researchers with assemblages that include fire-cooked eggshell should gently but thoroughly clean the eggshell and attempt to identify fragments that show minimal signs of burning or charring after they have been cleaned.

Secondly, eggshell fragments that appear darkened or charred can be checked for the delamination and mammillary cone damage that are characteristic of fire cooking using a SEM.

For best results when checking for fire cooking, researchers should select fragments that appear burned even after being cleaned, though our study showed that visible discoloration was not a perfect predictor of whether a fragment would show microscopic evidence of fire cooking.

Thirdly, the presence of fire-cooked eggshell at archeological sites may be used as a strong line of evidence indicating human occupation of a site. Large concentrations of fire-cooked eggshells are unlikely to occur in most natural situations. The high temperatures needed to cause mammillary cone damage would rarely occur naturally except in some instances of wild fires. Large concentrations of naturally occurring fire-cooked eggshell would result only if a wild fire occurred at a nesting site, in which case other geographical and biological factors should indicate this. Fire-cooked eggshell may therefore be used alongside other lines of evidence to argue for human occupation at sites where clearly identifiable artifacts are scare. Fire-cooked eggshells may be particularly useful to archeologists studying foragers and other mobile groups whose sites are particularly ephemeral.

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