Title: An often overlooked resource: Ostrich (*Struthio* spp.) eggshell in the archaeological record

Abstract:

Ostrich (*Struthio* spp.) eggshells are present in archaeological assemblages in many regions of Africa and Asia. However, and unlike other artifacts and ecofacts, there are no standardized guidelines for observing and recording non-ornamental ostrich eggshell. Here, we review prior research that focuses on facets of the taphonomic history of ostrich eggshell assemblages, and we document results from our actualistic studies of the changes in color that occur when ostrich eggshells are heated. We further propose some guidelines for recording ostrich eggshell in archaeological contexts, which include burning categories and quantification methods. These guidelines are intended to facilitate the development of large, comparative, and standardized ostrich eggshell data sets that will contribute to our understanding of site taphonomy and past human behavior.

Keywords: eggshell; taphonomy; fragmentation; quantification; burning; actualistic research

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1. Introduction

Ostriches (*Struthio camelus*) are commonly seen today throughout the woodlands, savannas, and grasslands of sub-Saharan Africa. However, their geographic distribution was much wider in the past, and ostriches (*Struthio* spp.) additionally extended throughout northern Africa, the Arabian Peninsula, and southwestern, southern, and central Asia. Ostriches are the largest living bird, and they also lay the largest egg. The size and robustness of ostrich eggs made them an important resource for humans, providing both food and a durable technological material. Ostrich eggshell (OES) is commonly present in archaeological assemblages throughout these regions, likely as a result of both the nutritional value and technological utility associated with ostrich eggs (Blinkhorn et al. 2015; Janz et al. 2009; Kurochkin et al. 2010; McBrearty and Brooks 2000; Mitchell 1996; Wadley 1993; Wang et al. 2009). The ubiquity of OES in archaeological assemblages suggests that the eggs, and their shells, were likely important resources for past peoples, and therefore fragments of OES should provide valuable data for reconstructing many past human subsistence practices, technological diversity, and potentially symbolic systems and social networks. However, aside from OES bead manufacturing and preservation (e.g. Kandel and Conard 2005; Orton 2008; Plug 1982), there is currently no standard rubric for recording and reporting OES recovered from archaeological contexts. The absence of standardized recording procedures inhibits comparative research of OES assemblages, and their behavioral and taphonomic correlates, between different archaeological occupations from different sites.

Here we review the archaeological literature discussing OES, and present a preliminary guide for describing non-ornamental OES from archaeological assemblages. These suggestions include qualitative and quantitative descriptions of OES fragments and guidelines for identifying heat-mediated modifications. We propose these descriptions as a starting point to standardize the recording of archaeological OES with the aim of generating large, comparable datasets that will contribute towards understanding, and differentiating between, taphonomic agents and human action in the archaeological record (Dominguez-Rodrigo 2008; Gifford-Gonzalez 1991).

2. Background

2.1. *Ostriches and their eggs*

The following short summary follows from many (Bertram 1979; Donegan 2002; Maclean 1985; Newman 2002). Ostriches are well-known as distinctive, large, flightless birds that may stand up to 2 m tall, and can grow up to 130-160 kg. The males are territorial and compete for small flocks of females, whose number varies with the local environment. Often, the male and his females scrape out a communal nest, where collectively the females lay their eggs. Reports vary widely on the number of eggs each female may lay for each nesting, and some nests have been reported to have up to 40-60 eggs. The male and females share responsibility for incubation. However, Bertram (1979) recognized that one female can only incubate about 20 eggs at a time, with the others often being pushed out of the nest; the dominant female avoids pushing out her own. The eggs hatch in about 40-50 days.

Ostrich eggs are large: each weighs between 1 and 1.5 kg, contains roughly 2,000 calories (equivalent to about 24 domestic hen eggs), and provides a rich source of protein and fat (including important monounsaturated, saturated, and polyunsaturated fatty acids) (Di Meo et al. 2003; Sales et al. 1996; Sinanoglou et al. 2011). In this regard, ostrich eggs were likely an important food source for hunter-gatherers. Moreover, and provided that the ostriches were not guarding the nest, the eggs would have been a gatherable resource that would not have required additional technology. Only

minimal technology, a hammerstone, is necessary for breaking into the shells.

Interestingly, while ostrich eggs appear to have been a widely used resource, bones of ostriches themselves are rarely found in archaeological sites. For example, only isolated finds are documented in Middle Stone Age assemblages of Ysterfontein 1 (Avery et al. 2008) and Varsche Rivier 003 (Steele et al. 2016) and from the Late Acheulean assemblage of Duinefontein 2 (Cruz-Uribe et al. 2003), all in the Western Cape Province, South Africa. Ostrich bones are virtually absent in Asian assemblages (Janz et al. 2009). The lack of evidence for ostrich carcass processing is surprising, because ostriches would provide a large package of nutrient-rich meat and associated tissues (Belichovska et al. 2015; Horbanczuk et al. 2003; Horbańczuk et al. 2004).

2.2. In archaeological assemblages

2.2.1. OES beads and other uses as ornamentation

Beads are perhaps the best known OES artifacts. They are ubiquitous throughout many regions of Africa and Asia during the Terminal Pleistocene and the Holocene (Mellars et al. 2013; Miller 2012; Miller and Willoughby 2014; Wang et al. 2009). They begin appearing in eastern Africa after 50,000 years ago or so (Ambrose 1998; Miller and Willoughby 2014), although a more extensive dating program, including direct dating, is needed to assess their antiquity in southern Africa (Steele et al. 2016; Villa et al. 2012).

The manufacturing of OES beads has been ethnographically recorded and extends into the present. OES beads have been documented as important exchange items in southern Africa (Wiessner 1984, 2002, 1977), providing archaeologists with potential insight into past social networks (Ambrose 1998; Miller and Willoughby 2014; Mitchell 1996; Sadr 2003; Smith et al. 2001; Wadley 1993; Wang et al. 2009), although Pargeter et al. (2016a,b) challenge the validity of this kind of analogy, particularly as we move further back in time.

As cited above, OES beads have been frequently discussed in the literature, and therefore we focus on other aspects of ostrich eggshells here. In summary, Plug (1982) provided an early recording scheme for OES beads based on their type, manufacturing stage and completeness. Subsequently, Kandel and Conard (2005) and Orton (2008) offered more detailed descriptions, including standardized coding schemes, of all stages of the OES bead manufacturing process. Kandel and Conard (2005) and Miller (2012) provide detailed outlines for recording many additional aspects of OES beads, including size, mass, color, and preservation. Wilmsen (2015) provides a recent discussion of the behavioral, natural, analytical, and taphonomic factors affecting bead sizes and their distributions.

Apart from OES beads, OES pendants, painted OES, and engraved OES have also been identified in the Middle and Later Stone of southern African. OES pendants are known from Later Stone Age contexts in Namaqualand (Dewar 2008). Decorated and painted OES pieces have also been recovered from late Middle Stone Age contexts at Apollo 11 in Namibia (Vogelsang et al. 2010). Engraved OES is present (but rare) in the archaeological record from ~ 60,000 years ago (Texier et al. 2010, 2013), and appears much more frequently in Later Stone Age and historical contexts (Humphreys and Thackeray 1983; Rudner 1953). It is suggested that these engravings generally occur on OES flasks.

2.2.2. OES containers

OES flasks are containers made from eggs that have been perforated and emptied. One perforation at the tapered end of the egg is the most common form, although some OES flasks demonstrate a perforation along the middle, and some display multiple perforations. The perforation(s) are achieved by using one or a combination of drilling, punching, hammering, or grinding (Kandel 2004: 386). These containers are most frequently associated with the storage of water, but were also used to store ground specularite, OES fragments, and ant larvae (Henderson 2002; Humphreys 1974; Kandel 2004; Silberbauer 1981). OES flasks are common ethnographically (Marshall 1976; Silberbauer 1981) and during the Later Stone Age of southern Africa (Deacon et al. 1978; Deacon and Deacon 1999; Rudner 1953), although much less so during the Middle Stone Age (Henshilwood et al. 2001; Texier et al. 2010; Vogelsang et al. 2010).

Kandel (2004) explored some of the taphonomic factors, specifically surface modifications, that result from human and carnivore actions on OES by conducting experiments that included feeding ostrich eggs to carnivores, and reviewing ethnographic data to attempt to distinguish the agents of modification. He concluded that there is significant overlap in the types of modifications made by human and carnivore agents, and emphasized the importance of context for identifying notched OES pieces as flask mouth rims. Kandel (2004: Table 3) provides some guidelines for identifying human action, which include a well-stratified context with minimal evidence of carnivore activity, a complete or refitted OES aperture, additional clear human modifications, such as engraving, decoration, use-wear, or external modifications (e.g. stopper), residues of the past contents, and multiple similar examples. As a result of his study, Kandel (2004) concludes that conchoidal fracturing indicating percussion from the outside or chipping, bevelling or grinding of the edges may not provide sufficient evidence of a flask mouth when in isolation.

2.2.3. Description and quantification

The relative abundance of OES fragments has been investigated in some archaeological analyses. At Blombos Cave, the grams of OES and then the grams of OES per cubic metre of excavated material are presented for the three main Middle Stone Age stratigraphic groupings at the site (Henshilwood et al. 2001). At Ysterfontein 1, grams of OES were presented for the three main Middle Stone Age stratigraphic groupings at the site; following Humphreys (1975), these weights were divided by a “typical” empty ostrich egg weight to produce an estimate of the number of eggs necessary to account for the weight (Avery et al. 2008). The OES weight was also compared to the weight of marine mollusks throughout the stratigraphy, allowing for a higher resolution comparison of the data (Avery et al. 2008). OES is much more abundant relative to marine mollusks in the middle and upper layers of the site. Human occupation appears to be less intense in the layers, compared to the lower layers. Avery et al. (2008) concluded that this high abundance of OES could indicate that hyenas played a significant role in accumulating those materials. A detailed taphonomic analysis could address this issue.

At Spitzkloof, OES are presented as grams per stratigraphic layer, and then as grams per excavated bucket of each stratigraphic layer, and these densities are presented relative to bone densities (Dewar and Stewart 2012). At Varsche Rivier 003, OES are presented as grams per stratigraphic layer, and then as grams per excavated litre of material (Steele et al. 2016). In both instances, these densities can be compared to other materials from the sites, facilitating studies of changing patterns through the sequence.

The Diepkloof Rock Shelter sample has been analyzed to the highest resolution, which is expected because of the engraved OES pieces found in Middle Stone Age contexts there. In addition to presenting the number of fragments per each stratigraphic unit, the fragments were sorted into three

size categories, presented by stratigraphic unit (Texier et al. 2013). Data on the “thermal alteration” is presented for their initial sample (Texier et al. 2010). These data are presented alongside detailed descriptions of the engraving found on this important assemblage.

2.2.4. Previous investigations into the effects of heating on OES

While many archaeologists have noticed variation in the coloration of OES fragments in archaeological assemblages (personal observations), only a few studies that we know of have explored the causes of this variation (Table 1 and SOM Table 1). Although their research was conducted for non-archaeological purposes, Janssen et al. (2011) provide an initial systematic investigation of the effects of heat exposure on OES fragments. They heated fragments of OES in a laboratory oven at incremental temperatures (between 200° and 800°C) for progressive durations (5 to 60 minutes), and present results on changes in mass and color. In sum, they found that most changes occurred by 30 minutes of exposure to heat, although they tested exposures up to 18 hrs. Relevant to archaeological OES fragments, the shells turned “orange yellow/yellow ochre” at 200°C for 30 minutes and “amber/antique brown” at 375°C for 30 minutes. At temperatures of 550°C and above, the fragments turned from blue, to grey, to white and lost their structural integrity. Finally, they concluded that temperature was more important than duration; five minutes of heating was generally sufficient to cause coloration changes. Unfortunately, Janssen et al. (2011) heated only two fragments with each treatment, and they present only a few photos of their results. Therefore, it is difficult to assess the range of variation in possible discolorations with each treatment and to use their photos for coding archaeological materials.

McLarty (2013) provided a follow up study where she exposed fragments of OES to direct laboratory flames in two high temperature ranges (400-600°C and 950-1050°C) for progressive durations (1 to 60 minutes). In the lower temperature range, the fragments immediately darkened and reddened and then with duration acquired a steel blue-grey color with iridescence; at 400-600°C, duration had an impact on color formation. At the highest temperatures (950-1050°C) the fragments were all uniformly grey or white, a change that occurred even with minimal exposure to this hot flame. Unfortunately, McLarty (2013) provided an image of only one fragment for each treatment, limiting our ability to assess variation (which is important because their 1 minute example is much darker than longer duration examples) and to use the photos for coding archaeological materials.

The analysis of the archaeological OES assemblage from Diepkloof provided a basis for additional studies into the relationship between OES color and heat. On the basis of preliminary heating experiments, Texier et al. (2010) concluded that the discoloration of the ostrich eggshell fragments was due to heating, and they coded ostrich eggshell fragments as 0-4 based on if they were their natural color, orange, red, black, or grey.

Texier et al. (2013) provided additional details of their heating studies. They heated OES fragments in a laboratory oven to moderate incremental temperatures (100-480°C) for 20 minutes each. Like the other studies, they found that around 400°C OES acquires a grey, iridescent color. Texier et al. (2013) presented the coloration changes associated with specific temperatures as values obtained from a colorimeter and as color names obtained through comparison with a Munsell color chart. However, they do not present photos of their results. Importantly, Texier et al. (2013) conducted an extensive refit study with their OES assemblage. They found that different colored pieces, interpreted as having been heated to different temperatures, refit; based on this evidence, they concluded that the OES fragments were accidentally heated by campfires post-depositionally.

Finally, Kandel and Conard (2005) indicate that they conducted a series of treatments to try to understand the blackening (presumably heating) of OES beads during their manufacturing. They regulated the oxygen concentration and manipulated the organic content of the fires in order to produce the range of color variation commonly seen in archaeological assemblages, and they examined the color variation found on fragments naturally burned by a brush fire. They conclude that “a low to moderate temperature under a reducing atmosphere with the addition of organic materials” (pgs. 1717-1719) allowed them to control the color outcomes. High temperatures and long exposure were detrimental to the OES. Because these heating studies were not the focus of their larger study, no further details were provided.

Table 1

Summary of the colors recorded for tested temperatures in previous studies and the current study.

Temperature (Celsius)	Previous studies	This study (Munsell names)	This study (Munsell codes)
Control	Janssen et al. 2011: A - White	Kiln: pale yellow	2.5Y 9/4
100	Texier et al. 2013: pale yellow		
150	Texier et al. 2013: pale yellow	Indirect fire: pale yellow	
200	Janssen et al. 2011: C - Orange yellow/Yellow ochre; Texier et al. 2013: yellow	Kiln: pale yellow to yellow; Indirect fire: pale yellow to orange yellow	2.5Y 9/4, 9/6, 8/6; 10YR 7/8
250	Texier et al. 2013: yellowish red		
260		Kiln: brownish yellow, yellowish brown, strong brown	10YR 6/6, 6/8, 5/8; 7.5YR 5/8
290	Texier et al. 2013: dusky red		
300		Kiln: yellowish brown, strong brown, light yellowish brown	10YR 6/6, 6/8; 7.5YR 5/6, 5/8; 2.5Y 6/4
340	Texier et al. 2013: light yellowish brown		
352		Kiln: brownish yellow, pale yellow, light gray	10YR 6/8; 2.5Y 7/4, 7/2; 5Y 7/3
360	Texier et al. 2013: light gray		
375	Janssen et al. 2011: E - Amber/Antique brown		
380*on sand bed	Texier et al. 2013: weak red	Kiln: light brown gray, grayish brown, gray, slightly iridescent	2.5Y 6/2, 5/2; 5Y 5/1
400	Texier et al. 2013: gray		
427		Kiln: gray, light gray, blue iridescent, friable	2.5Y 6/1; 7.5YR 6/1; 7.5R 6/1 2.5Y 7/1; 2.5YR 7/1; 7.5YR 7/1 closest to blue
440	Texier et al. 2013: light bluish gray		
480	Texier et al. 2013: pale blue		
550	Janssen et al. 2011: G - Iridescent sky blue/Venetian		

	blue
400-600	McLarty 2013: reds to steel blue, going from short to long
700	Janssen et al. 2011: I - Matte light neutral gray/Pratt's Payne's gray
800	Janssen et al. 2011: K - White
900-1050	McLarty 2013: all uniformly grey and 'calcined'

Munsell names and codes were acquired from Munsell Color (1949).

3. Actualistic studies of heating and burning

3.1. Heating OES in a kiln

To further document the color changes that may be observed when OES is heated, we started a series of treatments similar to those conducted by Janssen et al. (2011) and Texier et al. (2013) (Table 1 and SOM Table 1). To expand on their work, we aimed to assess the range of variation potentially present by documenting a set of 12 pieces of OES for each heat treatment and to explore longer durations, which may be more comparable to heating by a campfire. We purchased fragments of OES from Floeck's Country Ranch in Tucumari, New Mexico (www.floeckscountry.com); the ostriches that produced the eggs were born and raised on that ranch. Larger pieces of shell were broken and we made sets of 12 fragments for each treatment, 6 larger (to allow for breaking in two and reheating one half) and 6 smaller. All fragments were labeled on the inside, convex surface with their set number and sequentially numbered within that set. The membranes of many of the shells were intact. The samples were photographed as sets, with their labels visible as well as with their external, convex surfaces visible. This documented the specimens in their original form, and also ensured that we could recreate the specimen numbers if they burned off during heating. The mass of each sample was then recorded using an archaeometry scale measuring to the tens of thousandths of a gram.

Using a Skutt Automatic Kiln (Model KM-818) we heated sets of 12 OES fragments using the parameters outlined below. The pieces were set up in numerical order so that three small and three large were convex-side (inner surface) up, and the others placed convex-side (external surface) down. Pieces were photographed in place so that again their numbers could be reconstructed if they burned off during heating. After each heating, the kiln was not opened until it reached room temperature. The pieces were photographed in place before being bagged and returned to the laboratory, where they were photographed and weighed. The results are presented in Table 2 and Figure 1.

Table 2

Results from heating fragments of OES in a kiln; see also Figure 1 and Supplementary Materials. The Supplementary Material also provides detailed descriptions of each heating schedule.

Maximum temperature (Celsius)	Duration (minutes)	Set	Description
200	120	2	<i>External surface:</i> consistent rich, yellow; some variation between pieces in the depth of the color and one piece in particular stayed quite light <i>Inner surface:</i> minimal discoloration

			<i>Membranes:</i> curled around edges but fairly intact <i>Preservation:</i> likely very good
204	180	6	<i>External surface:</i> consistent rich, yellow; some variation between pieces in the depth of the color and some pieces in particular stayed quite light <i>Inner surface:</i> minimal discoloration <i>Membranes:</i> curled around edges but fairly intact <i>Preservation:</i> likely very good <i>Notes:</i> consistent with Set 2, despite the longer duration
260	180	5	<i>External surface:</i> yellowish brown to brownish yellow <i>Inner surface:</i> burnt orange <i>Membrane:</i> curled around edges but intact <i>Preservation:</i> likely very good
300	120	4	<i>External surface:</i> yellowish brown to brown, pores darkened <i>Inner surface:</i> dull grey – loss of color <i>Membrane:</i> mostly intact, dark, deep brown <i>Preservation:</i> likely very good
352	180	3	<i>External surface:</i> light tan to some orange yellow; pores appear quite dark <i>Inner surface:</i> light and chalky when not protected by membrane <i>Membrane:</i> mostly gone, when present, dark brown <i>Preservation:</i> moderate; all pieces intact, but feel slightly de-mineralized
388	180	7	<i>External surface:</i> medium brown-grey, slight iridescence, many pores darkened <i>Inner surface:</i> light and chalky when not protected by membrane <i>Membrane:</i> mostly flaked off, dark brown when present <i>Preservation:</i> moderate; all pieces intact, but feel slightly de-mineralized, cracking present <i>Notes:</i> some pieces are cracked, indicating the beginning of shape distortion
427	180	1	<i>External surface:</i> medium to dark grey with iridescent sheen <i>Inner surface:</i> dark steely grey; very friable and fragile; some spalled by planing during heating and when handled afterwards <i>Membranes:</i> almost always burned off <i>Preservation:</i> likely poor

We can offer a few observations. First, our color changes appear to follow Janssen et al. (2011) closely. The samples heated to 200°C in both studies appear a very similar deep yellow color. Janssen et al.'s samples heated to 375°C appear to be along the continuum of our 300°C and 350°C of dulling and darkening, and particularly the notable darkening of the pores. The inner surfaces of their 375°C samples appear quite comparable to our 300°C and 350°C surfaces when the membrane is no longer intact.

Second, neither Janssen et al. nor our study were able to consistently reproduce the deep ochre red

colors visible in the Diepkloof specimens (Texier et al. 2013). From their descriptions, it seems that Texier et al. (2013: Table 3) were also unable to produce this ochre red color using an oven for heating. Third, none of the studies using ovens or kilns produced black pieces, a color which is commonly observed on archaeological fragments and on beads (personal observations). Initial studies by Kandel and Conard (2005) indicated that altering the availability of oxygen and organics is necessary to blacken OES, and kiln does not provide the correct conditions. Fourth, their conclusion is supported by the variation seen on our kiln samples, where proximity to the ventilation holes in the kiln, which allow oxygen to enter, may be influencing the final coloration.

Fifth, at high temperatures (above ~400°C), OES becomes very friable. This has important implications for its preservation, or lack thereof, in the archaeological record. If pieces are heated to these temperature ranges, then their friable, fragile state means that any post-depositional disturbances, including trampling and site cleaning, will fragment them to the point of invisibility. It remains to be seen if hearths can heat OES to this degree, which will go some ways towards addressing if these specimens have been lost or OES is rarely heated to this temperature. In sum, while the oven and kiln studies are informative, we suggest that studies using hearths accompanied by thermocouples will provide the best way forward.

3.2. Heating OES in a fire

To further explore the effects of heat and fire on OES coloration and taphonomy, we conducted two actualistic burning studies. The first study exposed fragments of OES directly to a hearth fire and recorded temperature and color change. For the second study, OES fragments were buried under 5-8 cm of sand and indirectly exposed to a hearth fire for a long duration to imitate a potential camp fire.

OES for this study was acquired from Cape Point Ostrich Farm (<http://capepointostrichfarm.com/>), Western Cape, South Africa. One eggshell was used for this study, originally weighing 1380 g (including the yolk). The shell alone weighed 271.2 g and was broken into 31 fragments using a rock. 13 of those fragments were used for the study.

Temperatures were recorded using an RS Pro RS52 Digital Thermometer and an RS Pro 1000 mm Cable K Type Thermocouple. Although both products were advertised as being able to record temperatures greater than 800°C, they only succeeded in recording temperatures up to ~ 200°C. The study took place at Traveller's Rest in the Cederberg, Western Cape, South Africa. Fires were constructed in a stone and concrete fire pit, using hardwood purchased from Traveller's Rest. Sand from the nearby dry river bed was used to bury the OES fragments.

3.2.1. Direct exposure to fire

A large fire (~ 50 cm in diameter) was constructed in the middle of the fire pit and fed with fresh logs as needed. Roughly 45 minutes after the fire had been lit, three OES fragments were placed near the center of a fire. All fragments were exposed to temperatures of greater than 200°C on the side nearest to the flame. After 15 minutes, substantial color changes had occurred and the fragments were removed from the fire and left to cool overnight. Subsequently the fragments were photographed and cataloged (Figure 2).

3.2.2. Indirect exposure to fire

Ten OES fragments were buried under 5-8 cm of sand in an enclosed ~ 40 cm x 40 cm area (Figure

3A). A fire was built on top of the sand, and when sufficient coals were created, they were spread across the entire surface (Figure 3B). The fire itself was covered with sand two hours after it had been started to prevent forest fires. Temperature measurements were taken after 60 minutes, 90 minutes, 120 minutes (once the fire had been covered with sand), and 600 minutes (the next morning). These measurements were taken along a transect through the middle of the hearth using the thermocouple (Figure 3A). The thermocouple is 10 cm long and was submerged about halfway, providing a temperature measurement at about 5 cm depth. The following morning, the fire pit was excavated and all of the OES fragments were recovered, cataloged, and photographed.

3.2.3. Results

Color changes occurred quite quickly in the OES fragments exposed directly to the fire, which is to be expected as hearth fires typically demonstrate temperatures in excess of 500°C (Bentsen 2013; Steffen and Mackie 2005), and congruent with the findings reported by Janssen et al. (2011) and McLarty (2013). These changes were most pronounced in the areas closest to the fire and, following Janssen et al. (2011) and the results of the kiln study above, demonstrate exposure to temperatures between 375°C and 550°C. There are notable color gradients across the OES fragment surfaces, indicative of how quickly the heat from the fire seems to dissipate (Figure 2).

The buried OES fragments were exposed to much lower temperatures than those in the direct fire study, and, predictably, the color changes were not as stark (Supplementary Table 2, Figure 4). Some fragments displayed little, if any, color changes, while two displayed brownish-yellow color changes along one edge that were similar to those noted by the kiln study above at 260°C. These fragments were located in the central area of the hearth, and were exposed to higher temperatures. The remainder of the fragments displayed pale yellowish color changes similar to those described by Janssen et al. (2011) and the kiln study at ~ 200°C.

4. Recording non-ornamental OES in archaeological assemblages

There is no standardized methodology for recording OES fragments from archaeological assemblages. Here we present a working guide for quantifying, recording, and describing archaeological OES.

4.1. Quantification

To provide basic quantification information, all of the OES fragments should be counted and weighed for each stratigraphic context/unit from a site. Moreover, we propose the Approximate Number of Eggshells (ANE) as an additional (derived) quantification unit. This unit divides the weight of OES fragments from a specific stratigraphic context/unit by the “typical” weight of an empty ostrich eggshell. While ANE will directly track the weight data, we find that the derived value of ANE is useful for subsistence reconstructions. ANE provides an indication of how many ostrich eggs accumulated within a specific archaeological context. With ANE we can more easily consider the egg as a consumed resource; for example, ANE can be more readily compared to the MNI of tortoises in an assemblage, allowing a consideration of the relative abundances for these two small gatherable resources.

Of course, identifying a “typical” weight is somewhat problematic, as there are several reported values for average OES weight, and, as noted by Wilmsen (2015) and others, the weight, shape, and size of the shell depend on a large number of factors, including diet and season of laying (Sales et al. 1996). We have identified four studies that describe average weights for OES (Table 3).

Humphreys (1975) notes that his sample is small and likely unrepresentative; however, it is the only value that comes from wild ostriches. Both Humphreys (1975) and Kandel (2004) use values determined from OES container/flasks and not whole eggshells, although the difference is not likely to be significant. Keffen and Jarvis (1984) note that their average weight measurement comes from domesticated ostriches only, as do Di Meo et al.'s (2003). The latter's value is also the only measurement to come from outside of southern Africa (Italy). The differences between the average OES weights obtained from these studies introduce complications for producing ANE values. However, we prefer Di Meo et al.'s (2003) value, which provides the largest average OES weight and is based on the largest sample size. ANEs derived using Di Meo et al.'s (2003) value would provide the most conservative estimate, which is desirable considering the known and unknown taphonomic and behavioral variables affecting archaeological assemblages.

Table 3

A summary of recorded masses of whole, empty ostrich (*Struthio camelus*) eggshells.

Mean (g)	Number of Eggs	Source	Location	Reference
222.2 +/- 27 (179.7-292.8)	19	Domestic	South Africa	Keffen and Jarvis 1984
238 +/- 37	104	Domestic	South Africa	Kandel 2004
248.6 +/- 21.8 (211.2-277.8)	9	Domestic	South Africa	Orton 2008
259 (215-300)	13	Domestic	Africa	Texier et al. 2013
271.71 +/- 25.3	7	OES containers in a collection	South Africa	Humphreys 1975
295 ^a	582	Domestic	Italy	Di Meo et al. 2003

^a As the heaviest mean weight provided, we recommend that this value be used to calculate the Approximate Number of Eggshells (ANE) preserved in an OES assemblage.

4.2. Fragmentation and density

Standardized recording of OES fragmentation and densities within defined stratigraphic contexts will facilitate comparisons between different strata from the same site, and between different sites, increasing the potential of OES to inform on behavioral and taphonomic factors. We propose the use of a simple fragmentation index, where the number of OES fragments is divided by their mass for each analytical context, which could be per bucket or per stratigraphic context (Collins 2015; Dewar and Stewart 2012). This measure is easy to observe and provides an indication of the degree to which the OES assemblage is fragmented within a defined context.

Density refers to either the number of OES fragments or the mass of fragments within a given volume. Here we suggest observing the number of OES fragments per litre of sediment and the mass of the OES fragments per litre of sediment for specific strata. The results of these analyses would be a table that presents: number of fragments per context, mass per context, litres of sediment per context, then fragmentation as counts per mass, and then density as counts per litre followed by mass per litre. Context can vary with research questions, with excavation bucket or stratigraphic unit being the most helpful (see Steele et al., 2016: Table 18 for an example).

4.3. Coding OES coloration

Burnt OES is ubiquitous within archaeological assemblages (Kandel and Conard 2005; Medina et al. 2011; Texier et al. 2010; Wilmsen 2015). Here, we propose a straightforward six-category system to identify and describe OES using color changes on the external surface (Table 4 and Figure 5). We focus on the external surface because our actualistic research, in line with the other published research on OES burning, documents that the external surface better withstands the destructive attrition associated with heating and therefore better reflects heating intensity. We modeled our burning categories on the coloration changes produced in our actualistic research and documented by previous researchers, and we have used these studies to identify the associated temperature range. We code each fragment based on the highest indicated temperature (so the furthest down on Table 4), which should provide information on the maximum temperature that the fragment was exposed to.

“Unburnt” OES is OES that demonstrates no evidence of heating, i.e. no heat-induced discoloration is present. “Yellow” pieces have light to deep yellow color, including some shades of orange into light ochre; these pieces were likely only lightly heated to about 200°C. “Red” fragments display a deep rich red and ochre color, which may shade into tan or auburn; these have been heated to slightly higher temperatures around 300-350°C. “Black” fragments display blackening somewhere on their surface; while these pieces are common in the archaeological record (personal observations), they have not been documented in the studies considered here (but see Kandel and Conard (2005), as discussed above). “Iridescent” or blue fragments demonstrate an iridescent to blue to dark grey hue on their external surfaces; often their inner surfaces are dark grey. These pieces have likely been heated to temperatures above 400°C. At this point, the pieces become quite friable; they are likely to be heavily fragmented in the archaeological record. “Grey-white” are those that appear calcined, presenting either a dark-grey color (with no iridescence) or white. They have a chalky texture and are much more friable.

Table 4

Proposed burning categories for recording individual fragments of ostrich eggshell from archaeological contexts. For these categories, the coloration is observed on any part of the external surface of the eggshell fragment. See Figure 5 for OES specimens demonstrating these categories.

Category	Description of the color visible on any part of the external surface of the fragment	Temperature range
unburnt	no (pre-depositional) discoloration	unheated
yellow	deep yellow, yellow-orange, yellow-ochre	~ 200°C
red	red, ochre, auburn, tan	~ 300-350°C
black	blackened	currently unknown
iridescent	iridescent shimmer, blue, fragment becoming friable	~ 400-550°C
grey-white	grey, white, calcined-appearance, very friable	> 550°C

5. Discussion and conclusion

OES is ubiquitous within the archaeological archives of southern and eastern Africa (McBrearty and Brooks 2000; Mitchell 1996; Wadley 1993; Willoughby 2007), and is becoming increasingly

prominent in descriptions of Central Asian archeology (Janz et al. 2009; Kurochkin et al. 2010; Wang et al. 2009). However, OES has generally been haphazardly reported, and limited to discussions of OES beads, flasks, and artifacts. While the latter are important, they need to be complemented with research driven by taphonomic and behavioral questions to provide a more comprehensive understanding of how and why OES is present in archaeological contexts.

Here we have proposed some basic quantification methods that should be incorporated into future research conducted on OES assemblages. These include recording the fragmentation and density of OES specimens, as well as calculating the Approximate Number of Eggs (ANE). Standardizing the collection and reporting of OES data from archaeological contexts will facilitate comparative research between sites and provide better insights into the role of ostrich eggs within past human subsistence and technological systems. Moreover, ANE acknowledges the potential of ostrich eggs as a gatherable resource and provides an important step in further understanding the role of ostrich eggs in past subsistence strategies.

We conducted actualistic research to complement previous research documenting heat-mediated color changes in OES. The kiln study documented the color changes associated with increased temperatures in a controlled setting. In addition, by heating 12 samples in each set, and illustrating both surfaces of each sample, we can assess the range of variation produced. Samples were heated for 2-3 hours, a duration that likely more closely mimics the durations that OES pieces were exposed to in the past, such as when a campfire was built.

The results of our direct and indirect fire studies demonstrated color changes in OES that are concurrent with those recorded in the kiln, and reinforce the analogical framework for associating color changes in OES with maximum temperatures encountered by the fragments. Moreover, the color disparity seen across the outer surfaces of fragments exposed directly to fire is similar to fragments frequently encountered in archaeological assemblages (personal observations).

The indirect fire study provides taphonomic information on potential sources of post-depositional alteration in buried OES, whether by accident, or on purpose. With temperatures of over 350°C being recorded 5 cm below the surface of a fire (Bentsen 2013), it is not inconceivable that OES fragments may have been deliberately buried and then heated to transform their color. This method (burying the material and then building a fire on top to transform the material) has also been proposed for heat-treating rocks during the Middle Stone Age (Brown et al. 2009), and potentially offers a more controlled, and predictable, method of transforming the material than placing it directly in a fire.

This actualistic research has provided us with a framework for interpreting color changes in OES and their relation to temperature. Using this framework, we compiled a six-category guide for recording color changes in OES, and we have related each category to a temperature range. These categories are representative of key color variation in OES, and they can be easily and widely applied to future research on archaeological OES.

Our intent is to provide some additional guidelines for recording and analyzing OES. We hope, and expect, that this work will prompt future research focusing on different aspects of archaeological OES, and we are excited for the potential of documenting novel taphonomic and behavioral information from OES assemblages. More detailed descriptions of archaeological OES assemblages will provide valuable insight into past human foraging, social, and symbolic behaviors, and complement current high-resolution archaeological and analytical methods.

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Figure Captions:

Figure 1. OES samples heated in the kiln, organized by heating temperature. The external surface of four samples are presented from each set: the lightest, the darkest (i.e. the two extremes), and two representatives of the majority. See Supplementary Materials for images of all twelve samples in each set, showing the external and the internal surfaces (Photos: Patricia J. McNeill).

Figure 2. OES fragments exposed to direct fire. A-C are the specimens while in the fire. D-F are specimens after they had been removed from the fire. Note the color variation across each specimen. A corresponds with D, B with E, and C with F.

Figure 3. A) Plan view of the buried OES fragments prior to the construction of the fire. The black numbers 1-10 are the approximate locations of where the ostrich eggshell fragments were buried. The red numbers 1-3 are the approximate locations of where temperature measurements were taken and correspond with the temperature data in Supplementary Materials Table 2. B) Plan view of a temperature reading during the experiment.

Figure 4. OES fragments after the conclusion of the indirect fire study. The numbers correspond to their position, as indicate in Figure 3A. 1-3 were buried in the upper section, 4-7 were buried in the middle section, and 8-10 were buried in the lower section. Note the difference in color between the middle section, which was the center of the fire, and upper and lower sections, which were situated more towards the periphery of the fire.

Figure 5. Panel displaying the six different color categories proposed for coding OES fragments. A-B are examples of “unburnt” OES specimens from a mid-Holocene archeological context at Grassridge Rockshelter in the Eastern Cape of South Africa. C-D are examples “yellow” OES specimens from a mid-Holocene archeological context at Grassridge Rockshelter. E-F are examples of “red” OES specimens from a mid-Holocene archeological context at Grassridge Rockshelter. G-H are examples of “black” OES specimens from a mid-Holocene archeological context at Grassridge Rockshelter. I, specifically the left portion of the fragment, is an example of “iridescent” OES from the direct fire experiment discussed in 3.2.1. J-K are examples of “grey-white” OES specimens from a mid-Holocene archeological context at Grassridge Rockshelter.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Graphical abstract

Unburnt

Yellow

Red

1 cm

Black

Iridescent (Left)

Grey-White
(Centre, Right)