

AperTO - Archivio Istituzionale Open Access dell'Università di Torino

Incubated eggs in a Roman burial? A preliminary investigation on how to distinguish between the effects of incubation and taphonomy on avian eggshell from archaeological sites

This is a pre print version of the following article:

Original Citation:

Availability:

This version is available <http://hdl.handle.net/2318/1718848> since 2019-12-10T14:35:25Z

Published version:

DOI:10.1016/j.jasrep.2019.05.010

Terms of use:

Open Access

Anyone can freely access the full text of works made available as "Open Access". Works made available under a Creative Commons license can be used according to the terms and conditions of said license. Use of all other works requires consent of the right holder (author or publisher) if not exempted from copyright protection by the applicable law.

(Article begins on next page)

Manuscript Details

| | |
|--------------------------|--|
| Manuscript number | JASREP_2019_62 |
| Title | On the problem of identifying shells of incubated and hatched avian eggs from archaeological sites – a preliminary investigation |
| Short title | Identifying shells of incubated and hatched avian eggs from archaeological sites |
| Article type | Research Paper |

Abstract

Microscopic analyses can be used to determine whether fragments of eggshell come from hatched, incubated or non-incubated eggs. This information is essential for their interpretation since the developmental state of eggs often permits archaeologists to draw conclusions about the function of these finds at a site. However, what has often been neglected in previous studies is the fact that not only incubation but also taphonomy may affect the microstructure of shells. This preliminary study aims to demonstrate that taphonomic processes can in fact imitate features that are commonly interpreted as traces of incubation. The paper further introduces likely causes and one possible solution to this problem. The successful application of this technique on seemingly incubated eggs from a late roman burial of Ober-Olm (Germany) indicates that these shells were altered only by taphonomy and not by embryonic development as initially assumed. It is finally emphasized that the preliminary data of this investigation need to be validated in future research.

| | |
|---|---|
| Keywords | avian eggshell; incubation; taphonomy; eggshell quantification; late antiquity; burial sites; ritual |
| Corresponding Author | Benjamin Marcellus Sichert |
| Corresponding Author's Institution | University of Basel, Archaeology of the Roman Provinces and Integrative Prehistory and Archaeological Science (IPAS/IPNA) |
| Order of Authors | Benjamin Marcellus Sichert, Philippe Rentzel, Beatrice Demarchi, Julia Best, Arianna Negri, Sabine Deschler-Erb |
| Suggested reviewers | Marc McKee, James L. Hayward, Werner Müller, Frank D. Steinheimer, Alexander Heising |

Submission Files Included in this PDF

File Name [File Type]

cover_letter.pdf [Cover Letter]

manuscript_eggshell_jan_2019.docx [Manuscript File]

Fig_1.pdf [Figure]

Fig_2.pdf [Figure]

Fig_3.pdf [Figure]

Fig_4.pdf [Figure]

Fig_5.pdf [Figure]

Fig_6.pdf [Figure]

Fig_7.pdf [Figure]

Fig_8.tif [Figure]

Fig_9.tif [Figure]

Fig_10.pdf [Figure]

Fig_11.tif [Figure]

Fig_12.tif [Figure]

Fig_13.tif [Figure]

Fig_14.tif [Figure]

Fig_15.tif [Figure]

Fig_16.tif [Figure]

supplementary_figure_1.pdf [Figure]

Tab_1.docx [Table]

Tab_2.docx [Table]

Tab_3.docx [Table]

Tab_4.docx [Table]

figure_captions.docx [Supporting File]

supplementary_figure_caption.docx [Supporting File]

To view all the submission files, including those not included in the PDF, click on the manuscript title on your EVISE Homepage, then click 'Download zip file'.

On the problem of identifying shells of incubated and hatched avian eggs from archaeological sites – a preliminary investigation

Mr. Benjamin M. Sichert; benjam.sichert@stud.unibas.ch

University of Basel, Archaeology of the Roman Provinces (PRA) and Integrative Prehistory and Archaeological Science (IPAS/IPNA)

PD Dr. Philippe Rentzel; philippe.rentzel@unibas.ch

University of Basel, Integrative Prehistory and Archaeological Science (IPAS/IPNA)

Dr. Beatrice Demarchi; beatrice.demarchi@unito.it

University of Turin, Department of Life Sciences and Systems Biology; University of York, Department of Archaeology, BioArCh

Dr. Julia Best; bestj@bournemouth.ac.uk

Bournemouth University, Department of Archaeology, Anthropology and Forensic Science

Ms. Arianna Negri; arianna.negri@edu.unito.it

University of Turin, Department of Life Sciences and Systems Biology

PD Dr. Sabine Deschler-Erb; sabine.deschler@unibas.ch

University of Basel, Integrative Prehistory and Archaeological Science (IPAS/IPNA)

Abstract

Microscopic analyses can be used to determine whether fragments of eggshell come from hatched, incubated or non-incubated eggs. This information is essential for their interpretation since the developmental state of eggs often permits archaeologists to draw conclusions about the function of these finds at a site. However, what has often been neglected in previous studies is the fact that not only incubation but also taphonomy may affect the microstructure of shells. This preliminary study aims to demonstrate that taphonomic processes can in fact imitate features that are commonly interpreted as traces of incubation. The paper further introduces likely causes and one possible solution to this problem. The successful application of this technique on seemingly incubated eggs from a late roman burial of Ober-Olm (Germany) indicates that these shells were altered only by taphonomy and not by embryonic development as initially assumed. It is finally emphasized that the preliminary data of this investigation need to be validated in future research.

Keywords

avian eggshell; incubation; taphonomy; eggshell quantification; late antiquity; burial sites; ritual

1. Introduction

Various studies in the past have demonstrated that the analysis of avian eggshells from archaeological sites offers unique observations about human-animal interactions. What makes the inconspicuous remains often particularly appealing for detailed investigation is the fact that their microstructure can be used to determine whether the eggs were hatched, incubated or non-incubated. This information is important in archaeological reconstruction and sometimes can even be the basis for unexpected conclusions. For instance, Tõnno Jonuks et al. (2018) recently suggested that the function of two eggs in two 12th to 13th century AD burials of Kukruse (Estonia) may be closely connected with their developmental state. The fact that the eggs from the burials showed signs of advanced incubation is seen as an indicator of allegorical significance, possibly symbolizing beliefs about rebirth through the image of a bird emerging from its shell (Jonuks et al. 2018, 118-119). The authors further argue that the hatching egg represented a powerful symbol in Christian tradition, since it resembles the resurrection of Christ (Jonuks et al. 2018, 118.). In

analogy to this, or also to closely-related pagan concepts, incubated eggs may have been chosen deliberately for burials at Kukruse.

The case of Kukruse is not unique. Eggs have been found in a range of grave deposits across different cultures and periods and some of these likewise show traces of incubation (eg. Jakab 1979.). One example is the late roman burial site of Ober-Olm (Germany), which we will discuss in this paper. Similarly to the early medieval eggs from Estonia, it could be argued that the incubated state is the expression of an allegoric significance of these gifts. However, another possibility would be that the features that are currently interpreted as traces of incubation are not necessarily the result of embryonic development but may originate also from taphonomic processes after the egg's burial. This theory is partly confirmed by the earlier but relatively unknown findings of Werner Müller and Philippe Morel (Morel 1990. Morel/Müller 1997. Werner Müller, personal communication, June 2016.) and prompted the present investigation about eggshell taphonomy. The principal aim of this preliminary paper is not to present finished and comprehensive research on this problem but to sensitize archaeobiologists about the pitfalls of identifying incubated eggs and introduce them to one possible methodological solution.

2. Background: Biological principles and the identification of incubated eggs

During the incubation period the avian eggshell acts as a major source of calcium for the growing embryo (Chien et al. 2009, 527. Burley/Vadehra 1989, 284-286.). This is possible because the shell is primarily made up of calcite (approx. 96%), the most stable form of calcium carbonate (CaCO_3) (Chien et al. 2008, 84.). The embryonic resorption of shell calcium is based on its dissolution under acidic conditions (Chien et al. 2009, 528.). The chorioallantoic membrane (CAM), an extra-embryonic tissue (**Fig. 1**), which initiates mineral resorption after coming into contact with the inner shell membrane around the beginning of the second half of the incubation period, coordinates this process (Burley/Vadehra 1989, 284-286. Chien et al. 2009, 528-535. Beacham/Durand 2007, 1614.). The subsequent calcium dissolution visibly changes only the mammillary tips, resulting in their characteristic 'cratering' during incubation (**Fig. 2**). The reason for this peculiar pattern is the fact that the organic component (approximately 4%) of the eggshell, which is assumed to facilitate and guide the acid-

based calcium dissolution by weakening the shells mineral structure, is mainly present in the mammillary bodies (Chien et al. 2008, 85. Chien et al. 2009, 535-537.). It is important to note that it is not the entire eggshell surface that is affected by this process. The small area beneath the egg's air cell, usually located at the blunt end of the shell, is outside of the CAM's sphere of action (**Fig. 1**). Therefore, shielded by the air cell, this zone remains unaffected from calcium resorption while the mammillae of the remaining, considerably larger, part of the shell become increasingly cratered due to mineral loss (**Fig. 2**; Jakab 1979, 150-151. Morel 1990, 144. Beacham/Durand 2007, 1612.).

The dissolution of the mammillary bodies appears at different stages of incubation, usually in a uniform pattern (Marc D. McKee, personal communication, March 2016. Beacham/Durand 2007, 1614 and 1615 Fig. 3.). It should be noted, however, that certain exceptions to this usual appearance of embryonic calcium resorption may occur due to developmental disorders and variations; E. Bradley Beacham and Stephen R. Durand (2007) mention that in *“some uncommon instances, the air cell may become dislodged, resulting in inconsistent patterns of resorption.”* (Beacham/Durand 2007, 1614.). Moreover, for instance, a failure to turn eggs sufficiently during breeding can impede the CAM in advancing evenly across the shell-membrane, possibly causing a patchy pattern of corrosion, but then also leading in most cases to the death of the embryo (Tullett/Deeming 1987, 242-247.). Both anomalies seem to represent rather exceptional cases and a failure to turn eggs was reported to leave recognizable traces on shells (Romanoff 1960, 1134.).

Changes to the eggshell microstructure during incubation (or the lack of them) are already visible by low-magnification stereomicroscopy (30x - 40x magnification), and it has been proposed that the identification of an egg's developmental state during incubation can be achieved not only for modern eggs but also for archaeological finds (e.g. Jakab 1979. Morel 1982. Morel 1990. Morel/Müller 1997. Beacham/Durand 2007. McGovern et al. 2006. Conrad et al. 2016. Lapham et al. 2016. Jonuks et al. 2018.). Moreover, while details of the above described processes – for example the timing and degree of calcium removal – are known to be variable, the basic principles of embryonic mineral resorption seem to be similar for most or even all avian species (Blom/Lilja 2004, 365-366. Beacham/Durand 2007, 1612-1614. Chien et al. 2009, 537.). For the following preliminary study we therefore

propose that intra-avian comparisons are permitted to a certain extent. However, this premise needs to be validated in future investigations.

3. Materials and Methods

This study is based on the comparison of three groups of eggshells. Firstly the microscopic appearance of two modern hatched reference shells (goose and chicken) will be described. Since it is not the aim of this paper to present a detailed study on modern incubated eggs, the purpose of these two shells is to illustrate and quantify the observations of previous studies (eg. Jakab 1979, 149-151. Beacham/Durand 2007, 1612-1614.). The two modern hatched shells will be compared with known non-incubated chicken eggs from a modern compost heap. Changes observed on the latter's microstructures must be exclusively due to taphonomy. Finally, a comparison will be conducted with archaeological goose eggs from the late roman burial of Ober-Olm (Germany).

As has been outlined in the background section we assume in this preliminary investigation that the basic principles both of embryonic mineral resorption and taphonomic processes are comparable across different avian species.

3.1 Modern reference shells

For each species one successfully hatched egg of natural brood was obtained from small flocks of captive greylag geese (*Anser anser*) and domestic chicken (*Gallus gallus f. domestica*). To compare these reference shells with the archaeological specimens, they were prepared as follows. Firstly, membranes that blocked the view on the eggshell's internal surface had to be removed chemically while leaving the mineral structure intact. For this reason, shells were placed in glass containers with 5% sodium hydroxide solution and heated for 10 to 20 minutes in a boiling water bath as it is suggested for eggshells by Bušs and Keišs (2009, 91.). Afterwards, the shells were rinsed in water and dried at room temperature. Initially, the shells were observed in this state by stereomicroscopy. That way the position of corrosive features or their absence could be noted. Then, for reasons of comparability, the eggshells were randomly broken by hand to achieve roughly similar fragment sizes as those observed for the modern shells of the compost heap and the archaeological shells of burial 19.

The assessment of the broken shells was conducted in a standardized manner also applied to the compost eggshells and archaeological specimens (see sections 3.2 and 3.3): In a first step, the area in square millimeters (mm²) of each fragment was determined. This was conducted by placing the shell on millimeter paper and counting the number of covered squares. For pieces with a strong curvature, the actual area had to be estimated. Both the number of shell fragments and their total area in square millimeters (sum of individual shell fragment areas) served later as foundation for quantification. This was necessary because of the large variability of shell fragment sizes within the archaeological assemblages and the compost heap. After this preparation, each fragment of eggshell was assigned to one of the following five categories:

'surface uncorroded'

'surface mostly uncorroded with corroded zone(s)'

'surface mostly corroded with uncorroded zone(s)'

'surface uniformly corroded'

'not assessable'.

Finally, a number of fragments was selected for nano-imaging in a Nova NanoSEM 230.

3.2 Eggshells from a modern compost heap

Reference samples of exclusively taphonomically altered eggshells were recovered from a modern compost pile (site coordinates: 48°03'54.9"N 7°36'16.6"E), located 210 km to the south of Ober-Olm on the upper Rhine plane at the foot of the Kaiserstuhl hills near Freiburg i. Br. (Baden-Wuerttemberg, Germany).

The studied heap had been laid out in spring 2009 on formerly ploughed farmland and underneath a walnut tree. It was framed by a block construction of alternately longitudinal and transversely stacked, wooden logs, forming in top view a square of 1,15m. From its initial setting up the accumulating pile was never dug over or changed in any other way. It served a four-person-household for discarding mostly organic kitchen refuse, including eggshells, but almost no other animal remains. Moreover, small amounts of charcoal and ash were disposed on the compost heap. The eggshells came exclusively from non-incubated eggs, used for food preparation. For stratified sampling of the compost heap, a vertical section was cut through the pile. Samples of sediment and a minimum of 100 eggshell fragments were extracted

by hand from each layer of the structure (**Fig. 3**). An additional soil sample was taken from the pile's eggshell-free subsoil.

Measurements of the <0.5 mm sediment fraction of all samples were taken at the Geoarchaeological Laboratory of the IPAS, University of Basel. The analyzed parameters were the total carbonate content (by production of carbonic gas after reaction with HCl, i.e. Müller's calcimeter), the humus content (by colorimetric method using sodium fluoride as reagent), and the pH (with a pH-meter in a KCl solution). In addition, the organic content (loss on ignition; Davies 1974.) and the phosphate content (by colorimetric method using ammonium molybdate as reagent; Lorch 1940.) were measured.

The collected eggshells were handled with great care and any unnecessary chemical and physical strain was avoided. However, to remove attached sediment, they were rinsed carefully in water and dried at room temperature. A chemical removal of shell membranes was not conducted.

Assessment and quantification of the compost shells was identical to that carried out on the modern hatched reference shells described in section 3.1 (*Modern reference shells*). One additional recorded feature was the presence or absence of organic shell membranes.

3.3 Archaeological eggshells

The archaeological eggshells were recovered during excavations in 2001 from the burial of a middle-aged female (burial 19) at the late Roman cemetery of Ober-Olm (coordinates 49°57'14.8"N 8°12'22.3"E). The site dates between the second half of the 4th and the first half of the 5th century AD (Machura/Sichert 2015, 79.) and is proposed to belong to a rural estate nearby (Machura in prep.). **Figure 4** shows the location and arrangement of the eggshells in burial 19 upon recovery. Two eggs, still recognizable but heavily fragmented, lay slightly isolated at the deceased's left hand side (**Fig. 4: ④ and ⑥**). In the same area, but some centimeters closer to the dead, there was a chaotic assemblage of an unknown number of eggshells, partly covered by the remains of a rooster (**Fig. 4: ⑤**). During the excavation, shells were collected by hand. No sieving was applied and no soil samples were taken from the burial.

A preliminary identification by macroscopic comparison with modern reference eggs by Frank D. Steinheimer (ZNS Halle) suggests that the shells ④ and ⑥ come from

Anser anser f. domestica or its wild ancestor. Although shell thicknesses and curvatures of some fragments in assemblage ⑤ indicate the presence of one or more smaller sized egg(s) they likewise seem all to come from domestic or wild goose (Frank D. Steinheimer, personal communication, October 2018.). Peptide mass fingerprinting (PMF) was conducted on eight eggshell fragments from all assemblages of burial 19 using the methods detailed in Presslee et al. (2017). The analyses confirmed the identification of all eggshell fragments as Anseriformes (see spectrum in supplementary figure I).

The assessment of the eggshell fragments by stereomicroscopy was conducted in the above-described standardized manner by recording the number of fragments and their area in square millimeters (mm²) (see 3.1 *Modern reference shells*).

4. Results

4.1 *Modern reference shells*

The modern hatched eggs of goose and chicken were dominated by uniformly corroded surfaces both by number of fragments and their total areas in square millimeters (mm²) (**Tab. 1; Fig. 5**). However, the number and total area of uncorroded shells was higher in the chicken egg. Apart from this and other minor variations, it is notable that the two eggs of two different species show roughly similar percentages of uniformly corroded, uncorroded and patchily corroded surfaces (**Fig. 5**). Uncorroded shells came always from the air cell area at the egg's blunt poles. Fragments that displayed both corroded and uncorroded zones (**Fig. 2**) originated mostly from the small zone of transition between air cell area and the remaining surface. Only few shells from the eggs apex areas had patches of uncorroded mammillae within corroded zones. These shells were classified accordingly ('*surface mostly corroded with uncorroded zone(s)*'). Apart from that, the surfaces at the lateral sides and apex of both eggs were always corroded uniformly. Occasionally small spots of one to five intact mammillae occurred in between otherwise entirely uniformly-corroded shells. Since these small spots were rare and isolated, shells with this appearance were classified as '*uniformly corroded*'.

4.2 Modern compost heap

The excavation of the compost pile revealed an approximately 30 - 40 cm thick sequence of four layers, still framed by the pile's rotting lower wooden logs (**Fig. 3**). Below this zone was the sandy, slightly silty former topsoil-horizon on which the pile had been set. The location of the samples is marked in **figure 3**.

Although some bioturbation by roots and small mammals was observable in the section, it did not seem to have significantly affected the heap's stratigraphy. In fact, the comparatively low amount of turbation and the relative coherence of each sampling unit were also indirectly visible in the recovered fragments of eggshell: The shells were slightly more fragmented in the bottom layers of the heap than at the top (**Tab. 2**). Moreover, in the upper parts of the pile, the inner sides of the eggshells were often still covered by organic shell membranes (**Fig. 6; Fig. 7**). This hindered their microscopic assessment, particularly on specimens of layer I. With increasing depth the organic membranes became progressively decomposed and less frequent and eventually disappeared from shells in sample IV (**Fig. 6**).

The spatial timeline of fragmentation and organic decomposition described above was paralleled by signs of corrosion on the eggshells. Already the upper, youngest, sample contained some fragments that featured corrosion marks on mammillary tips (**Tab. 2; Fig. 5**). With increasing depth of samples, the finding of corroded shells became more frequent. Uniform dissolution patterns (**Fig. 8**) were observed in all samples, however, usually only at low frequencies and total areas in square millimeters (mm²). The majority of corroded shells displayed patchy patterns of corroded and uncorroded surfaces (**Fig. 9**).

Geochemical soil samples overall underlined the relatively low amount of turbation described above (**Tab. 3**). For instance, loss on ignition and humic substances were with 42% and 1,5 c.u. highest in sample I from the uppermost und thus least decomposed layer of the compost pile. Both values decreased with increasing depth – only loss on ignition in sample III with 20% breaks slightly ranks. Geochemical analysis further showed comparatively high calcium carbonate values in all layers (8-21%). Finally, measurements of the pH indicated an alkaline milieu (7,8-8,6) in the entire compost heap and below.

4.3 Archaeological eggshells

The microscopic structure of eggshells of all assemblages of burial 19 displayed signs of, often strong, calcium carbonate dissolution (**Tab. 4; Fig. 5; Fig. 10**). These corrosive features, however, often differed considerably from those on shells of the modern hatched reference eggs and reports about modern incubated eggs from literature and personal communications. *Uniform* corrosion, which appears most often in embryonic resorption was present only at very low frequencies and total areas (mm²) in all assemblages (**Tab. 4; Fig. 5; Fig. 11**). Instead, mostly *irregular* patterns of corrosion were observed (**Fig. 5, Fig. 10; Fig. 12**). These patchy surface appearances, which hatched reference shells displayed only at relatively low percentages, characterized the largest proportion of the shells from all assemblages of burial 19 (**Tab. 4; Fig. 5**).

Not only did the state of calcium dissolution vary strongly for neighboring mammillae in archaeological shells, some specimens from burial 19 also exhibited patches of excessively flattened mammillae (**Fig. 13**). In addition, mineral dissolution had affected some external surfaces of shells, which showed sporadically deep depressions on their external (convex) sides (**Fig. 14**).

Moreover, both on the inner and the outer sides of many shells, roots of plants had formed shallow grooves. There was no visible correlation between these grooves and specific states of the surrounding mammillary tips, which sometimes appeared uncorroded (**Fig. 15**) and sometimes corroded (**Fig. 16**).

5. Discussion

In the following discussion the likely reasons for taphonomic calcium dissolution on eggshells will firstly be presented and debated. Afterwards, approaches to gain more certainty for the distinction between taphonomic corrosion and embryonic mineral resorption will be introduced. In this section, the eggshells from the late roman burial 19 of Ober-Olm will serve as example of application. The results of the analysis will finally be evaluated for their interpretive implications considering the function of the eggs during funeral rituals.

5.1 Causes of taphonomic corrosion

In 1990, Philippe Morel drew attention to the possibility that the dissolution of the mammillary tips of archaeological eggshells may not only be a result of embryonic resorption but also of taphonomic processes (Morel 1990, 144-146.). This hypothesis was experimentally reinforced by Werner Müller, who applied droplets of acid on shells of modern non-incubated eggs and discovered that specimens treated that way displayed the same crater-like dissolution features as shells of hatched birds (Morel 1990, 144-146. Werner Müller, personal communication, June 2016.). The samples from a modern compost heap examined in this study now complement those pioneering findings, which unfortunately went unnoticed in later studies, and provide data from an actualistic environment that might be closer to the archaeological reality than artificial laboratory conditions.

Chicken eggshells from the compost pile clearly showed evidence of site-specific mineral loss and a subsequent cratering of mammillary tips, allegedly typical for incubation. This is because the centers of the mammillary bodies represent structural weak spots that are vulnerable to any corrosive attack, irrespective of whether caused by embryonic action during incubation or taphonomic weathering. As explanation for this taphonomic corrosion, Philippe Morel and Werner Müller suggested slightly acidic soil conditions (Morel/Müller 1997, 96). Yet, chemical analyses of the compost sediments indicate an alkaline environment in all layers of the pile (**Tab. 3**). This is even more surprising when considering that with the increasing depth of the samples, and thus with increasing age of recovered shells, the percentage of taphonomically altered fragments increases (**Fig. 5**). Corrosive processes thus seem to have occurred not only during the chemically-active phase, when the organic waste discarded together with eggshell started to decay, but also at later times. If the corrosion of the mammillary tips was based on acidic dissolution, this must have happened at a scale too small and too localised to have had an impact on the overall alkaline sediment. But how can such a localized process be explained?

In paleontologically-motivated experiments, Denise L. Smith and James L. Hayward (2010) investigated the possible role of bacteria in triggering eggshell deterioration. Their results and subsequent explanatory model was that *“bacterial decomposition of the eggshell protein matrix produces organic acids, which, in turn, dissolve the CaCO₃ of the shell. The dissolved CaCO₃ and NH₃ from protein degradation increase*

the pH of the surrounding sediment." (Smith/Hayward 2010, 324.). Another consequence of these processes is an increase in soil calcium carbonate (Smith/Hayward 2010, 320.).

This model may also be applicable to processes inside the compost heap. For instance, *B. subtilis* and *P. fluorescens*, which belong to the group of bacteria tested by Smith & Hayward, are known to exist in compost sediments (Tuomela et al. 2000, 173. Boulter et al. 2002, 665-669.).

To a certain extent the model above may also partially explain both the high pH and the soil calcium carbonate values in the pile. Yet, it is likely that these conditions cannot be explained by eggshell decomposition alone. In general, most compost heaps, after a first phase where pH decreases, turn alkaline when progressively more ammonium is released due to the decomposition of proteins by microorganisms (Tuomela et al. 2000, 173. Bilitewski/Härdtle 2013, 404-406.). Moreover, it should be remembered that in our compost heap ash had been disposed of, likely leading to an additional rise of soil calcium carbonate and alkaline pH. Nevertheless, bacterial action on the eggshells may have contributed to the overall measured values in the compost sediments and may have also been responsible for site specific dissolution features both on the shells of the modern pile and archaeological assemblages.

At the beginning of this study, the involvement of plant roots was considered to be another possible explanation for eggshell corrosion: It is well known that roots can change the pH in their surrounding sediment (Hinsinger et al. 2003, 43.). In the compost heap, visible roots were in fact present, however limited and rather confined to its lateral sides and the area underneath the structure. Moreover, root grooves on shells could not be observed, making this a less likely cause for direct mammillary dissolution on compost eggshells.

On the contrary, imprints of plant roots were frequent features on specimens from the roman burial. However, since no consistent correlation between zones of cratered mammillae and root grooves could be established in this case a connection is also currently excluded.

To summarize, both embryonic resorption and taphonomic corrosion are likely based on acidic dissolution processes, driven and modulated by the organic matrix of the shell, or by the empty channels it left behind. At this stage, we suggest that bacteria or other microorganisms are the most likely cause of taphonomic mineral loss. Due to

the complexity of such processes, however, our results cannot be considered final and we invoke more research efforts from interdisciplinary teams.

5.2 Strategies for distinguishing taphonomic and embryonic corrosion

Notwithstanding the precise causes of taphonomic corrosion, the shells from the compost heap demonstrate that the visible effects of these processes cannot be differentiated easily from embryonic calcium resorption. Nevertheless, it would be the wrong step to dismiss the possibility of assessing the developmental state of archaeological eggshells. In fact, Philippe Morel has previously presented approaches to distinguish both causes of mineral loss. In the following section these methods will be reevaluated and complemented with new results and strategies.

One of the techniques developed by Philippe Morel to identify the taphonomic origin of corrosion was based on the fact that an eggshell's blunt pole is usually shielded from the CAM by the air cell and in consequence from embryonic calcium resorption. He reasoned that the corrosion he observed on the blunt pole of archaeological shells thus could not be related to incubation (Morel 1990, 146.). This approach requires very favourable conditions of preservation and low degrees of fragmentation since it is necessary to assign shell fragments to their original position on the egg. Unfortunately, in most archaeological assemblages, including the burial of Ober-Olm, these requirements are not met. However, other ways to verify that taphonomic corrosion had taken place also exist: For instance, in the case of the roman grave finds, dissolution features observed on the shells' external (convex) sides (**Fig. 14**) likewise could not be related to incubation (Simone Häberle, personal communication, January 2017). Also, patches of excessively flattened mammillae (**Fig. 13**) may indicate weathering processes. Finally, according to Philippe Morel, extensive irregular corrosion patterns in general are also a result of taphonomy rather than incubation (Morel 1990, 146.).

All three of the above described features may allow the detection of taphonomic mineral loss. However, they do not exclude incubation. This is because shells of incubated and hatched eggs are also subject to taphonomic processes. For instance, it is possible that the originally uncorroded air cell area of a hatched egg becomes corroded during and after its embedding in archaeological structures. This secondary taphonomic calcium carbonate dissolution may then cause, for example, inconsistent

patterns of corrosion. Likewise, corrosive features at the shells external (convex) sides and patches of flattened mammillae can be observed as taphonomic dissolution on shells of hatched eggs (Smith/Hayward 2010, 320.). For this reason, additional approaches are needed to not only prove the occurrence of taphonomic processes but also to exclude prior incubation. One key to success in this matter may at least partly be an issue of quantification. This can be demonstrated with the eggshells from burial 19 (Ober-Olm): Although the shells of all eggs beside the dead largely bore marks that, according to the degree of mamillary corrosion, seemed to be related to advanced incubation or even hatching, the large total areas in square millimeters (mm²) with irregular patterns of dissolution were not consistent with the observations from modern hatched specimens (**Fig. 5**). Even when assuming that parts of the archaeological eggs may be missing, the recorded surface appearances cannot be brought into accordance with the proportions known from the reference specimens.

For earlier stages of incubation, the current data situation is less clear: It cannot yet be entirely excluded that early embryonic calcium dissolution may manifest itself with different corrosion patterns and proportions than those observed in the hatched reference specimens. However, observations by other scientists indicate that early embryonic resorption also appears according to uniform patterns (Marc D. McKee, personal communication, March 2016. Beacham/Durand 2007, 1614 and 1615 Fig. 3.). Furthermore, developmental variations and disorders, another possible cause of the encountered inconsistencies on the shells, are rather exceptional cases and seem unlikely to occur in more than one egg of the burial.

In combination with the fact that taphonomic corrosion is likely to have taken place, there are no firm arguments that point towards incubation. Indeed, the observed proportions of surface appearances show similarities with shells of non-incubated eggs from the modern compost heap (**Fig. 5**). The shells with both corroded and uncorroded areas appear in both groups more frequently and at larger total areas in square millimeters (mm²) than uniformly cratered shells.

For this reason, at this stage, all data indicate that the shells of the late roman burial 19 were not incubated at the time of the funeral or at least not incubated long enough to leave traces on the shell. However, the following section will show that this does not simplify the interpretation of these grave gifts.

5.3 The developmental state of eggs and their function during funerary rituals

Tönno Jonuks et al. (2018) suggested that information about the developmental state of eggs in burial deposits may help to identify their function during the funerary rituals. Based on this hypothesis it could be argued that shells of non-incubated eggs might have symbolized culinary gifts and remains of incubated or hatched eggs more abstract concepts instead. In fact, Christian writers in late antiquity have often emphasized the image of emerging life from the avian egg and drawn parallels to resurrection:

“The buried chick calls out loud from the egg’s inside; at this sound the grave splits open and its body rises (to live). That is to say, also the chick in its egg is a corpse. Its body promises our body resurrection.”

Epraem, Carmina Nisibena 103,65,18-19 (translated by Beck 1963, 92.)

It is possible that this image was integrated into late roman funerary rituals. However, it has to be noted also that this model may rather mirror modern western concepts and not necessarily past realities. For instance, it cannot be ruled out that partly incubated eggs may have been consumed, similar to practices in parts of Asia today (Magat 2002, 63.). On the other hand, a symbolic significance related to abstract concepts does not necessarily require physical incubation of the egg, for example, the custom of decorating children’s coffins with golden eggs, symbolizing life that is only temporarily trapped within the grave, was testified at the Swiss parish of Stammheim (Kt. Zürich) (Gattiker/Gattiker 1989, 44-45.). Despite this highly emblematic concept, the egg’s developmental state seemed to have been of no relevance for this ritual.

To summarize, it can be stated that information regarding whether an egg was not-incubated, incubated or hatched is indeed important but not the only aspect to be considered in the very complex discussion regarding their function during funeral rituals.

6. Conclusion

The study of eggshells from archaeological sites has a real potential to clarify aspects of people’s lifeways and deathways. However, the methodological limits of such studies need to be well understood. The analysis of eggshells from a modern

compost pile has shown that changes in the microstructure of shells are not necessarily related to incubation, as frequently assumed, but can also be 'imitated' by taphonomic processes. This makes it difficult to reliably identify the developmental state of eggs from archaeological sites. Quantifying corrosive appearances by means of shell fragment areas in square millimeters (mm²) may be one key to a more reliable identification of the developmental state.

It has to be stressed that this study is based on a small number of modern reference shells. The presented results thus need further verification and possible corrections. Future research will show if our approach for distinguishing between the effects of taphonomy and incubation proves to be successful.

Acknowledgements

This research would not have been possible without the assistance of many people. We want to thank Prof. Alexander Heising and Ms. Magdalena Machura (University of Freiburg (i. Br.), IAW), Dr. Frank D. Steinheimer (University of Halle (Saale), ZNS), Dr. Werner Müller (Université de Neuchâtel, Laboratoire d'archéozoologie), Dr. Heidemarie Hüster-Plogmann, Dr. Simone Häberle and Dr. Elizabeth Lizzie Wright (University of Basel, IPNA/IPAS), Ms. Evi Bieler (University of Basel, Nano Imaging Lab), Dipl. Biol. Ottmar Fischer (University of Freiburg (i. Br.), FZI), Prof. Marc D. McKee (McGill University), Ms. Sam Presslee and Prof. Matthew J. Collins (University of Copenhagen), Ms. Jorune Sakalauskaite (University of Turin), Ms. Lisa Bost, Fam. Stierstorfer and Ms. Lena Radau.

Funding: The species identification of the archaeological eggshells by peptide mass fingerprinting (PMF) was kindly supported by the project "Cultural & Scientific Perceptions of Human-Chicken Interactions". The authors gratefully acknowledge the use of the Ultraflex III MALDI-TOF/TOF instrument in the York Centre of Excellence in Mass Spectrometry, which was created thanks to a major capital investment through Science City York, supported by Yorkshire Forward with funds from the Northern Way Initiative.

References

Beacham/Durand 2007

E. B. Beacham/S. R. Durand, Eggshell and the archaeological record: New insights into turkey husbandry in the American Southwest. *Journal of Archaeological Science* 34, 2007, 1610–1621.

Blom/Lilja 2004

J. Blom/C. Lilja. A comparative study of growth, skeletal development and eggshell composition in some species of birds. *Journal of Zoology* 262, 2004, 361-369.

Beck 1963

E. Beck, Des heiligen Ephraem des Syrers Carmina Nisibena. *Corpus Scriptorum Christianorum Orientalium Scriptorum Syri* 103 (Louvain 1963).

Bilitewski/Härdtle 2013

B. Bilitewski/G. Härdtle, *Abfallwirtschaft. Handbuch für Praxis und Lehre*⁴ (Berlin 2013).

Boulter et al. 2002

J. I. Boulter/J. T. Trevors/G. J. Boland, Microbial studies of compost. bacterial identification, and their potential for turfgrass pathogen suppression. *World Journal of Microbiology & Biotechnology* 18, 2002, 661–671.

Burley/Vadehra 1989

R. W. Burley/D. V. Vadehra, *The avian egg. Chemistry and biology* (New York 1989).

Bušs/Keišs 2009

A. Bušs/O. Keišs, Method for identification of avian species by eggshell microstructure: Preliminary study. *Acta Universitatis Latviensis* 753, 2009, 89–98.

Chien et al. 2008

Y.-C. Chien/M. T. Hincke/H. Vali/M. D. McKee, Ultrastructural matrix-mineral relationships in avian eggshell, and effects of osteopontin on calcite growth in vitro. *Journal of Structural Biology* 163, 2008, 84–99.

Chien et al. 2009

Y.-C. Chien/M. T. Hincke/M. D. McKee, Ultrastructure of avian eggshell during resorption following egg fertilization. *Journal of Structural Biology* 168, 2009, 527–538.

Conrad et al. 2016

C. Conrad/E. L. Jones/S. D. Newsome/D. W. Schwartz, Bone isotopes, eggshell and turkey husbandry at Arroyo Hondo Pueblo. *Journal of Archaeological Science: Reports* 10, 2016, 566–574.

Davies 1974

B. E. Davies, Loss-on-ignition as an estimate of soil organic matter. *Soil Science Society of America Proceedings* 38, 1974, 150–151.

Gattiker/Gattiker 1989

E. Gattiker/L. Gattiker, *Die Vögel im Volksglauben. Eine volkskundliche Sammlung aus verschiedenen europäischen Ländern von der Antike bis heute* (Wiesbaden 1989).

Hinsinger et al. 2003

P. Hinsinger/C. Plassard/C. Tang/B. Jaillard, Origins of root-mediated pH changes in the rhizosphere and their responses to environmental constraints: A review. *Plant and Soil* 248, 2003, 43–59.

Jakab 1979

B. Jakab, Vergleichende Analyse der anlässlich von Ausgrabungen in Ungarn freigelegten Eierschalen-Funden, *Acta archaeologica Academiae Scientiarum Hungaricae* 31, 1979, 147–162.

Jonuks et al. 2018

T. Jonuks/E. Oras/J. Best/B. Demarchi/R. Mänd/S. Presslee/S. Vahur, Multi-method Analysis of Avian Eggs as Grave Goods: Revealing Symbolism in Conversion Period Burials at Kukruse, NE Estonia. *Environmental Archaeology* 23, 2018, 109-122.

Lapham et al. 2016

H. A. Lapham/G. M. Feinman/L. M. Nicholas, Turkey husbandry and use in Oaxaca, Mexico. A contextual study of turkey remains and SEM analysis of eggshell from the Mitla Fortress. *Journal of Archaeological Science: Reports* 10, 2016, 534–546.

Lorch 1940

W. Lorch, Die siedlungsgeographische Phosphatmethode. *Die Naturwissenschaften* 28, 1940, 633–640.

Machura, Sichert 2015

M. Machura/B. M. Sichert, Nischengräber des spätantiken Bestattungsplatzes von Ober-Olm (Lkr. Mainz-Bingen). *Berichte zur Archäologie in Rheinhessen und Umgebung* 8, 2015, 79-89.

Machura in prep.

M. Machura, Mittelkaiserzeitlicher und spätantiker Bestattungsplatz von Ober-Olm (Lkr. Mainz-Bingen).

Magat 2002

M. Magat, Balut: Fertilized Duck Eggs and their Role in Filipino Culture. *Western Folklore* 61, 2002, 63–96.

McGovern et al. 2006

T. H. McGovern/S. Perdikaris/Á. Einarsson/J. Sidell, Coastal connections, local fishing, and sustainable egg harvesting: Patterns of Viking Age inland wild resource use in Mývatn district, Northern Iceland. *Environmental Archaeology* 11, 2006, 187–205.

Morel 1982

P. Morel, Bestimmung eines Eierschalenfragments am Löffel Nr. 133. In: E. Riha/W. B. Stern, Die römischen Löffel aus Augst und Kaiseraugst. *Forschungen in Augst* 5 (Augst 1982) 10–11.

Morel 1990

P. Morel, Quelques remarques à propos de coquilles d'oeufs découvertes dans une tombe de l'époque augustéenne à Sion Petit-Chasseur. In: J. Schibler/J. Sedlmeier (Ed.), Festschrift für Hans R. Stampfli. Beiträge zur Archäozoologie, Archäologie, Anthropologie, Geologie und Paläontologie (Basel 1990) 141–146.

Morel/Müller 1997

P. Morel/W. Müller, Hauterive-Champréveyres 11. Un campement magdalénien au bord du lac de Neuchâtel. Étude archéozoologique. Archéologie neuchâteloise 23 (Neuchâtel 1997).

Presslee et al. 2017

S. Presslee/J. Wilson/J. Woolley/J. Best/D. Russell/A. Radini/R. Fischer/B. Kessler/R. Boano/M. Collins/B. Demarchi, The identification of archaeological eggshell using peptide markers. STAR: Science & Technology of Archaeological Research 3, 2017, 89-99.

Ridlen/Johnson 1964

S. F. Ridlen/H. S. Johnson, From Egg to Chick. A Guide to the Study of Incubation and Embryonic Development. Circular (University of Illinois, Agricultural Experiment Station) 878, 1964, 1-16.

Romanoff 1960

A. L. Romanoff, The avian embryo. Structural and functional development (New York 1960).

Smith/Hayward 2010

D. L. Smith/J. L. Hayward, Bacterial decomposition of avian eggshell: A taphonomic experiment. Palaios 25, 2010, 318–326.

Tullett/Deeming 1987

S. G. Tullett/D. C. Deeming, Failure to turn eggs during incubation: Effects on embryo weight, development of the chorioallantois and absorption of albumen. British Poultry Science 28, 1987, 239–243.

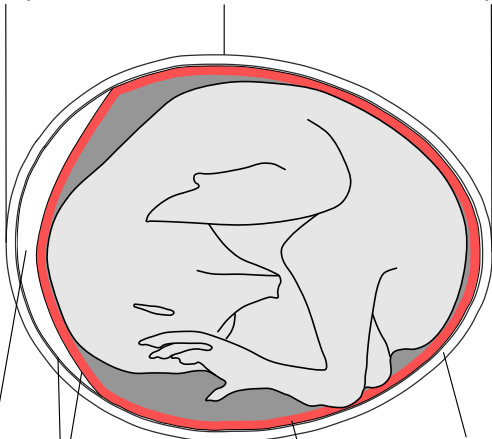
Tuomela et al. 2000

M. Tuomela/M. Vikman/A. Hatakka/M. Itävaara, Biodegradation of lignin in a compost environment: A review. *Bioresource Technology* 72, 2000, 169–183.

blunt pole

lateral sides

apex

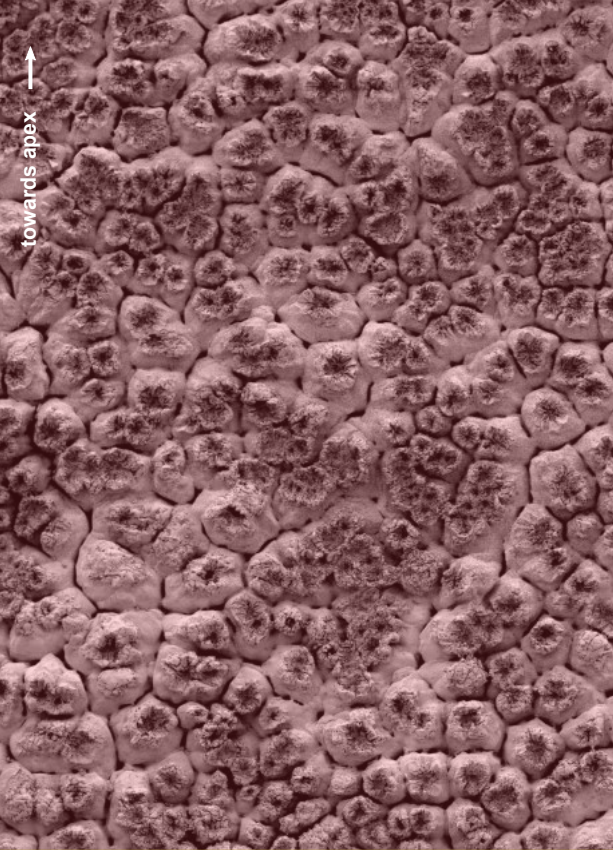


air cell

eggshell

shell membranes

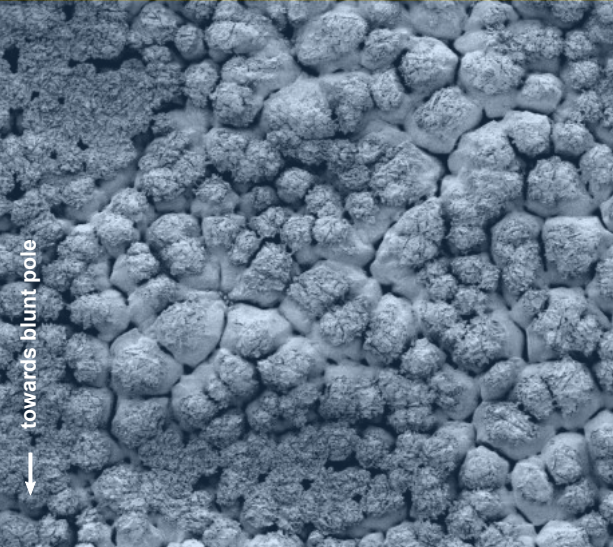
chorioallantoic membran



ZONE OF EMBRYONIC RESORPTION



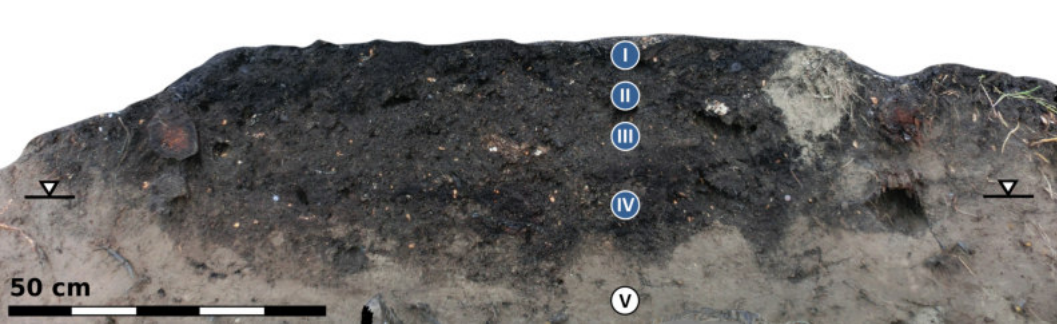
ZONE OF TRANSITION



AIR CELL AREA (SHIELDED FROM RESORPTION)

Mag: 50x 69,7x WD: 15 mm

400 μ m



I

II

III

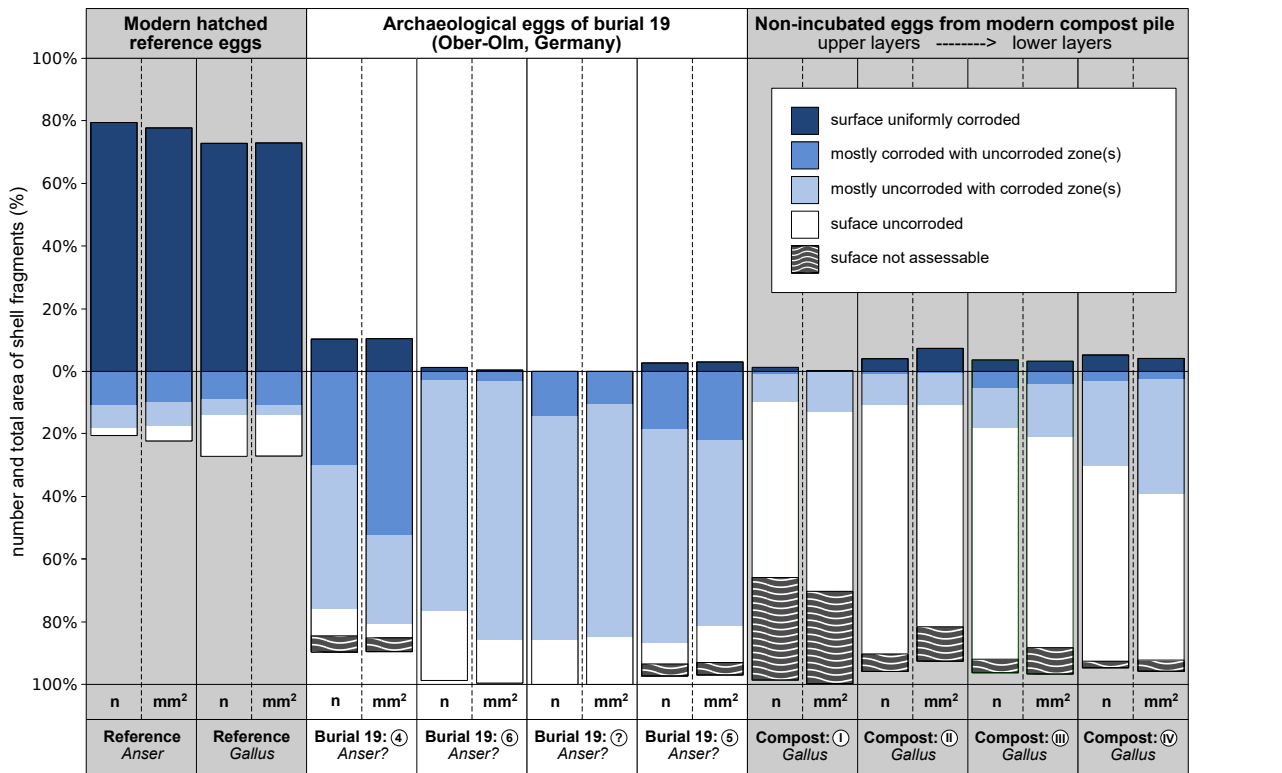
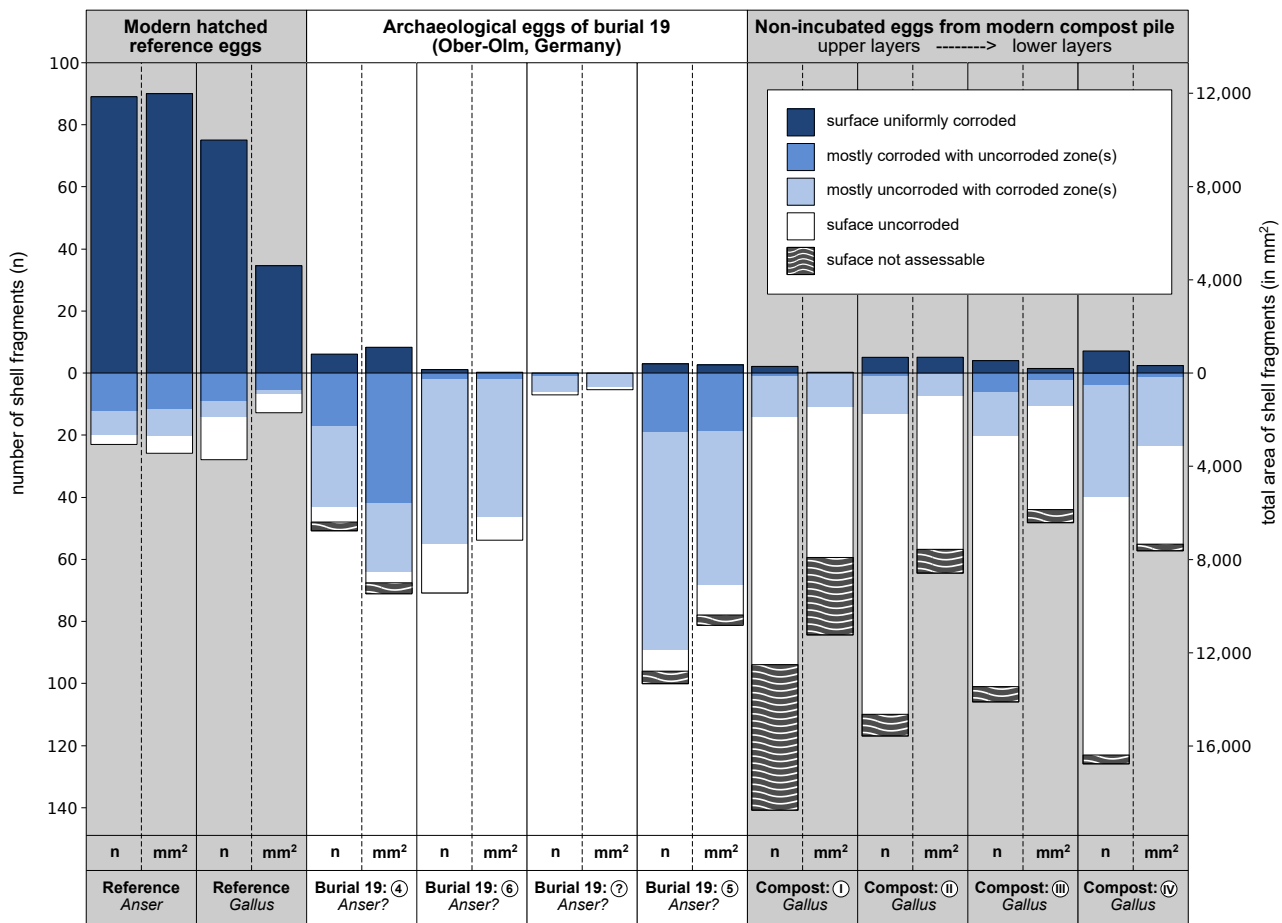
IV

V



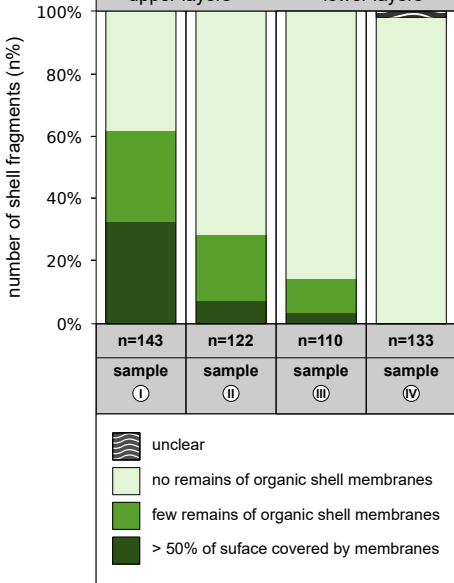
50 cm

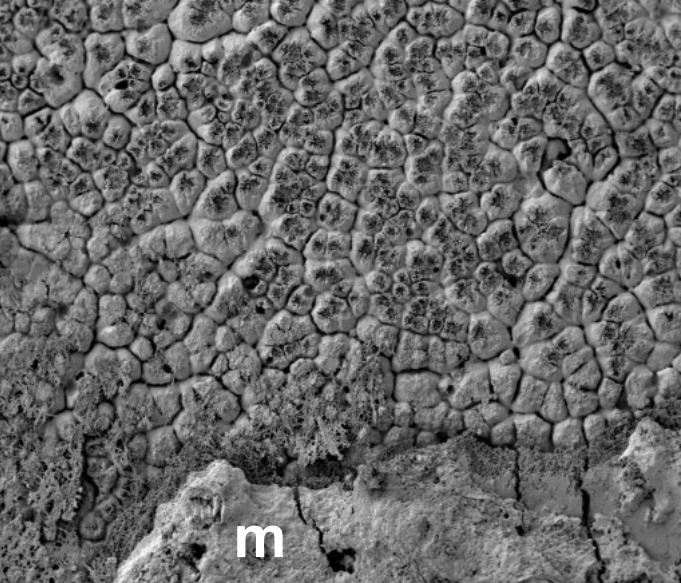




Modern eggshells from compost pile

upper layers -----> lower layers

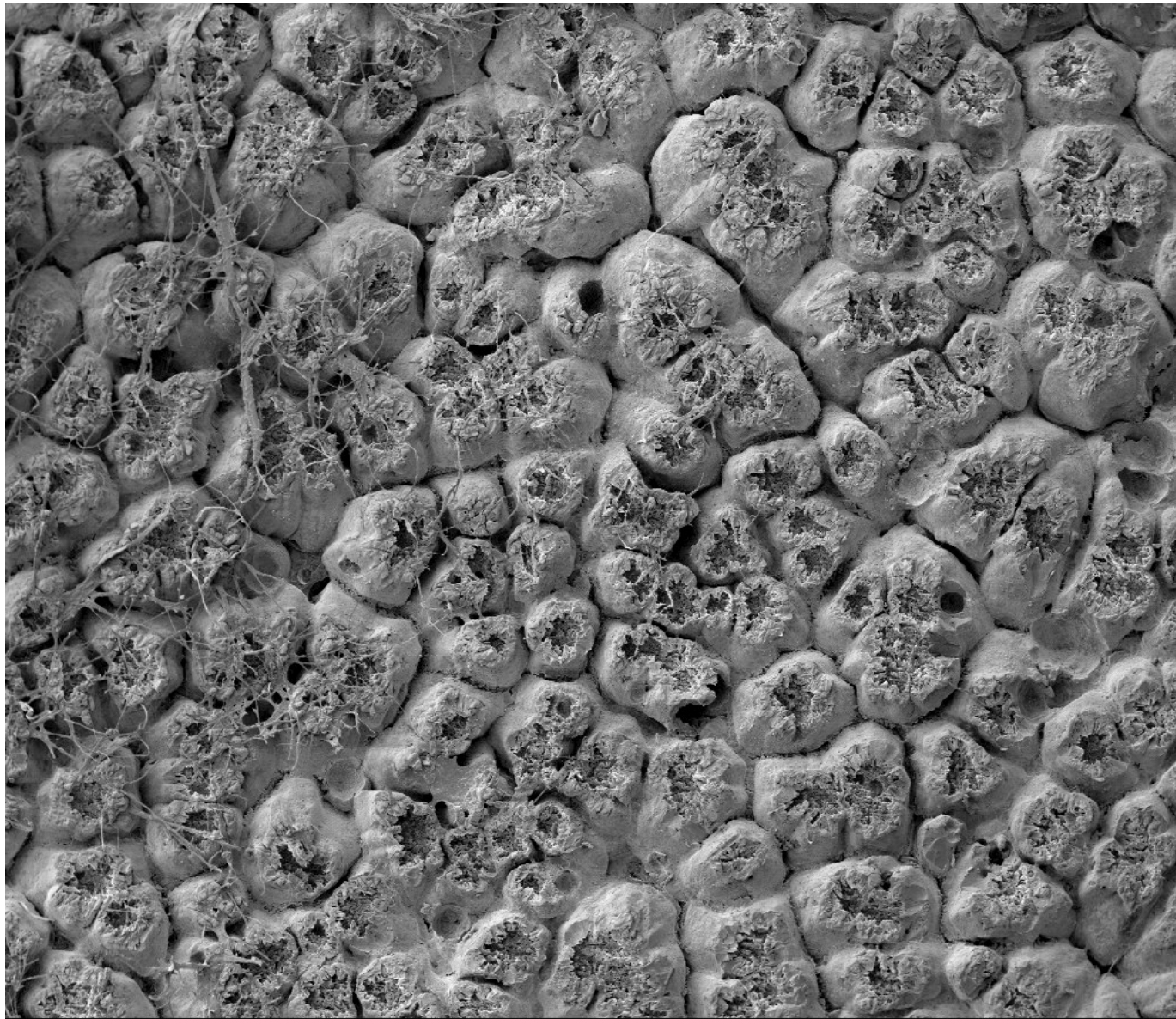




00166817

300 μm

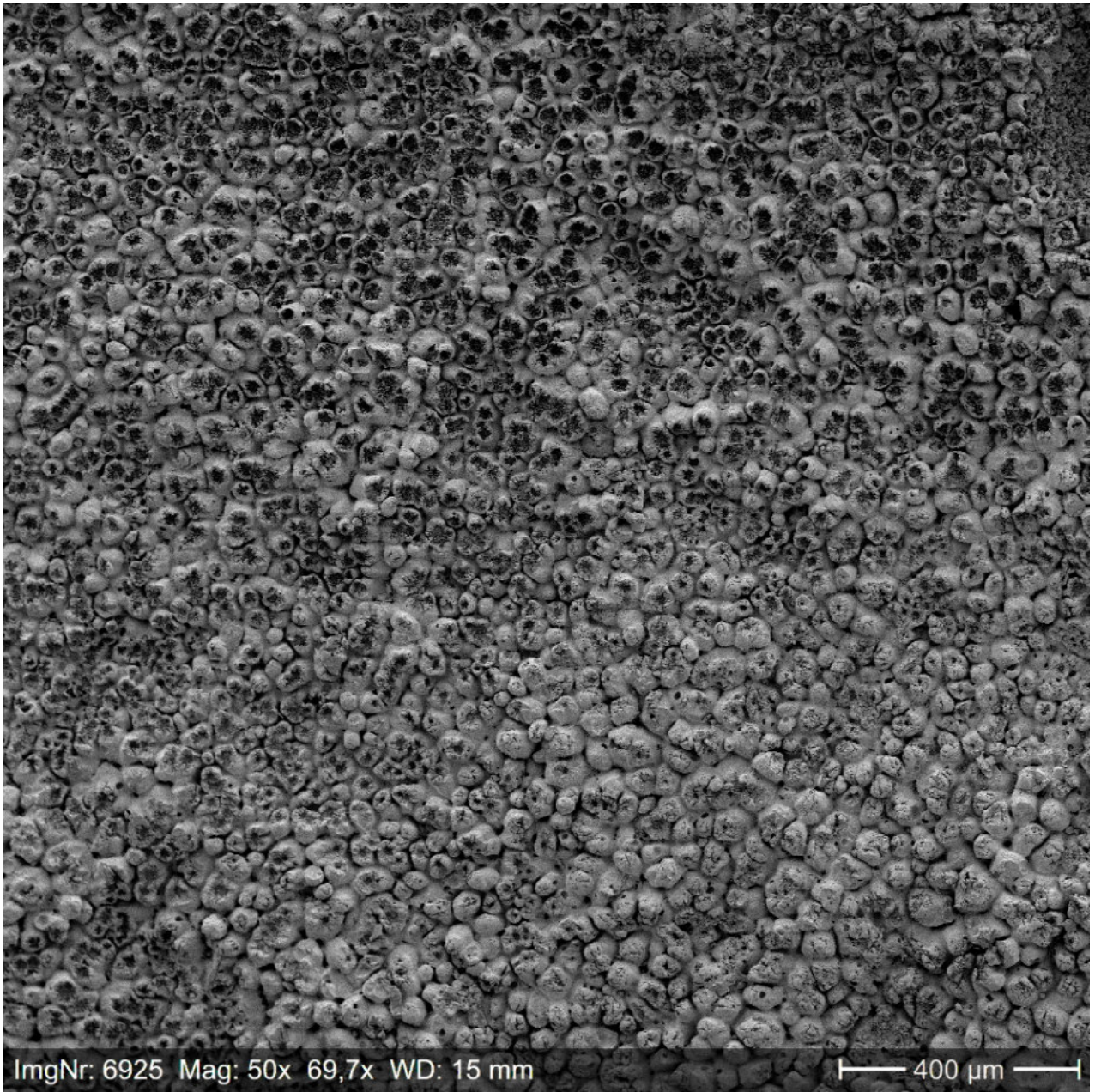
NANOIMAGING-LAB



00167554

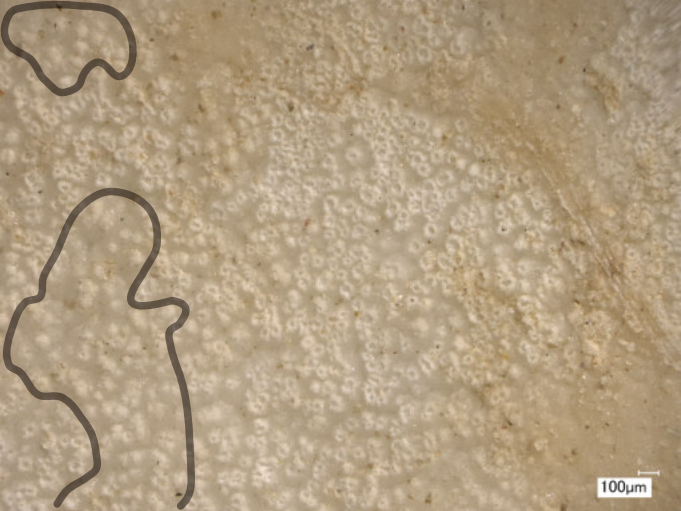
— 100 μm

NANOIMAGING-LAB



ImgNr: 6925 Mag: 50x 69,7x WD: 15 mm

400 µm



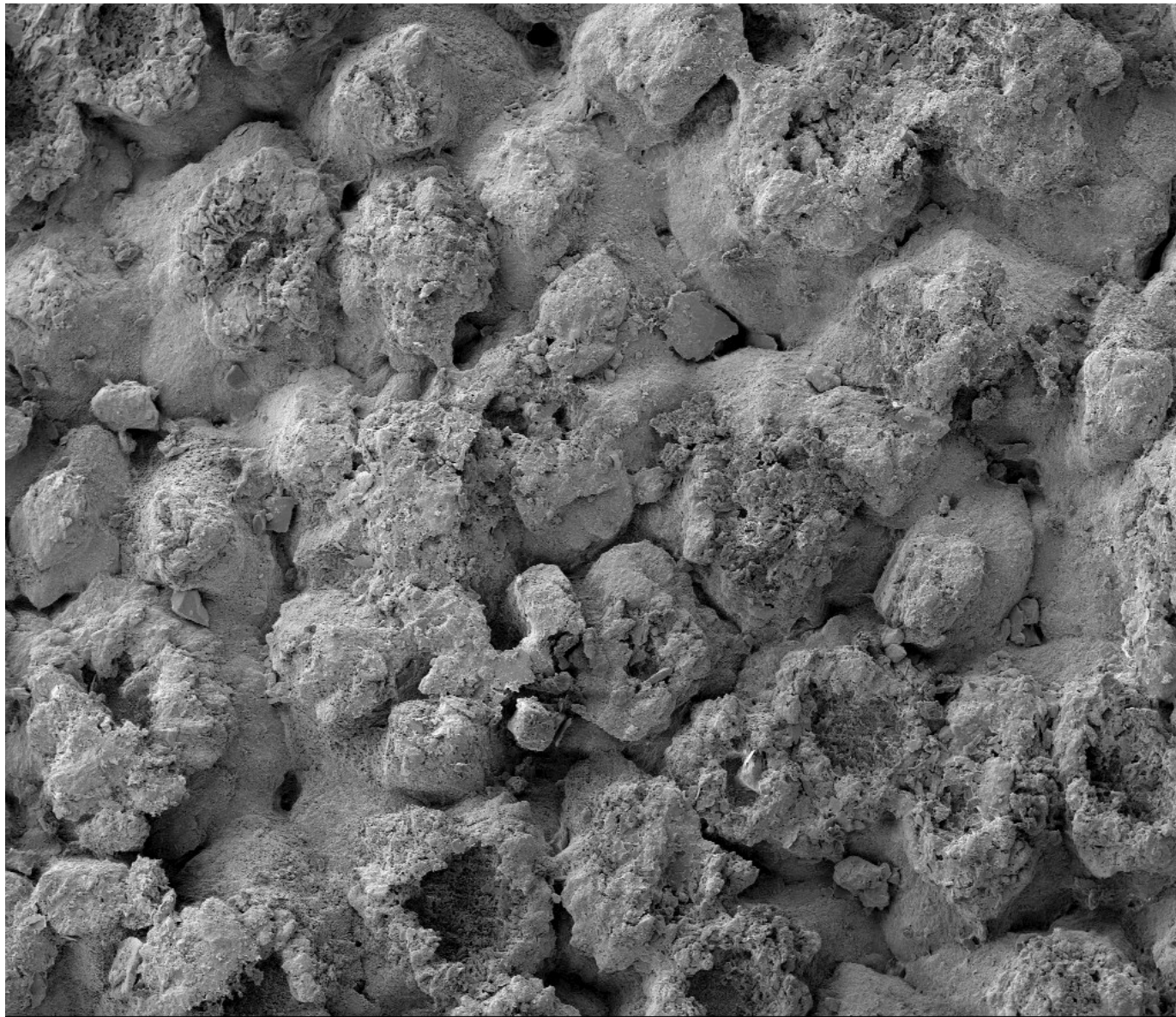
100µm



00166827

— 50 μm

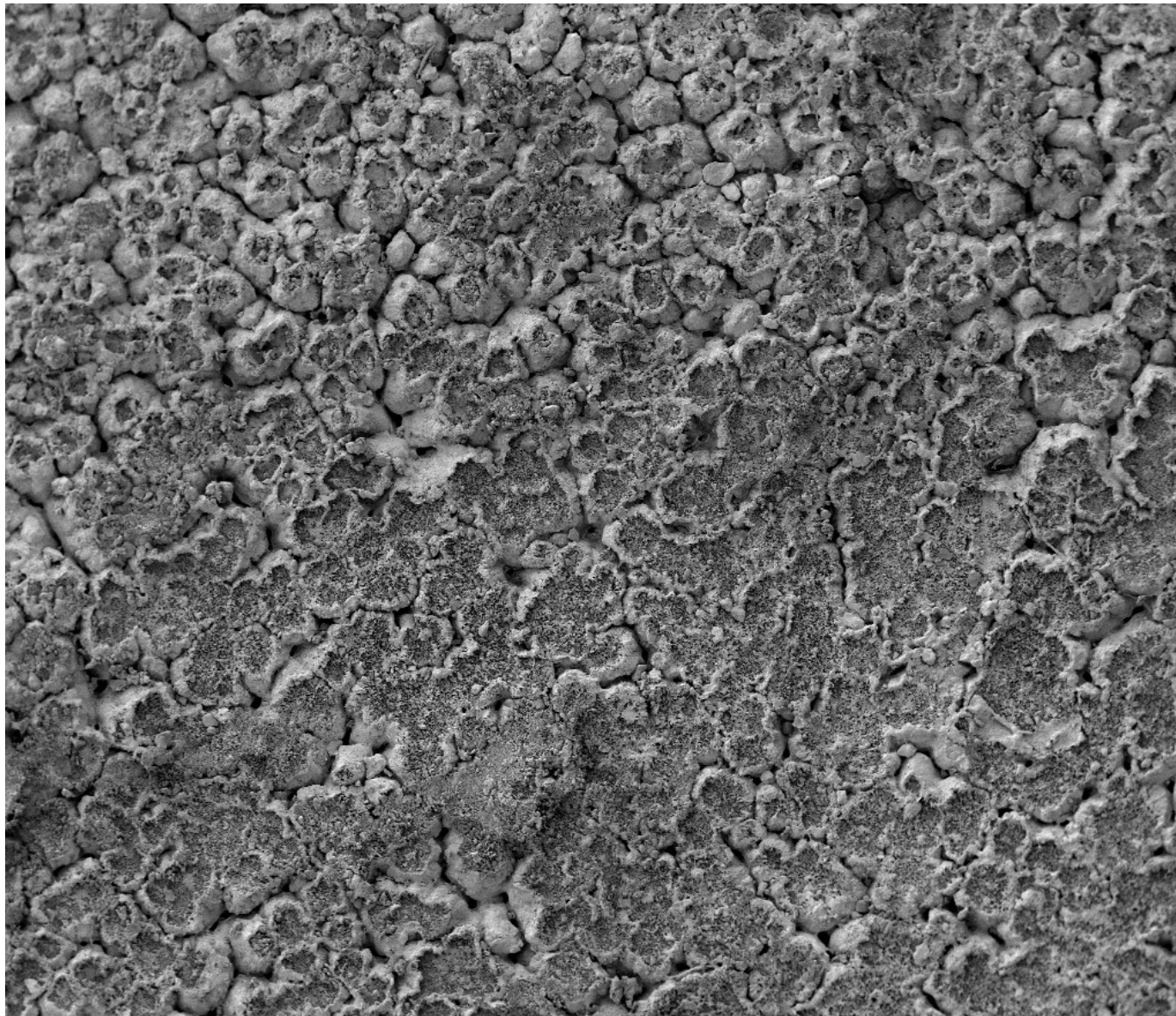
NANOIMAGING-LAB



00167547

— 50 μm

NANOIMAGING-LAB



00166824

————— 300 μm

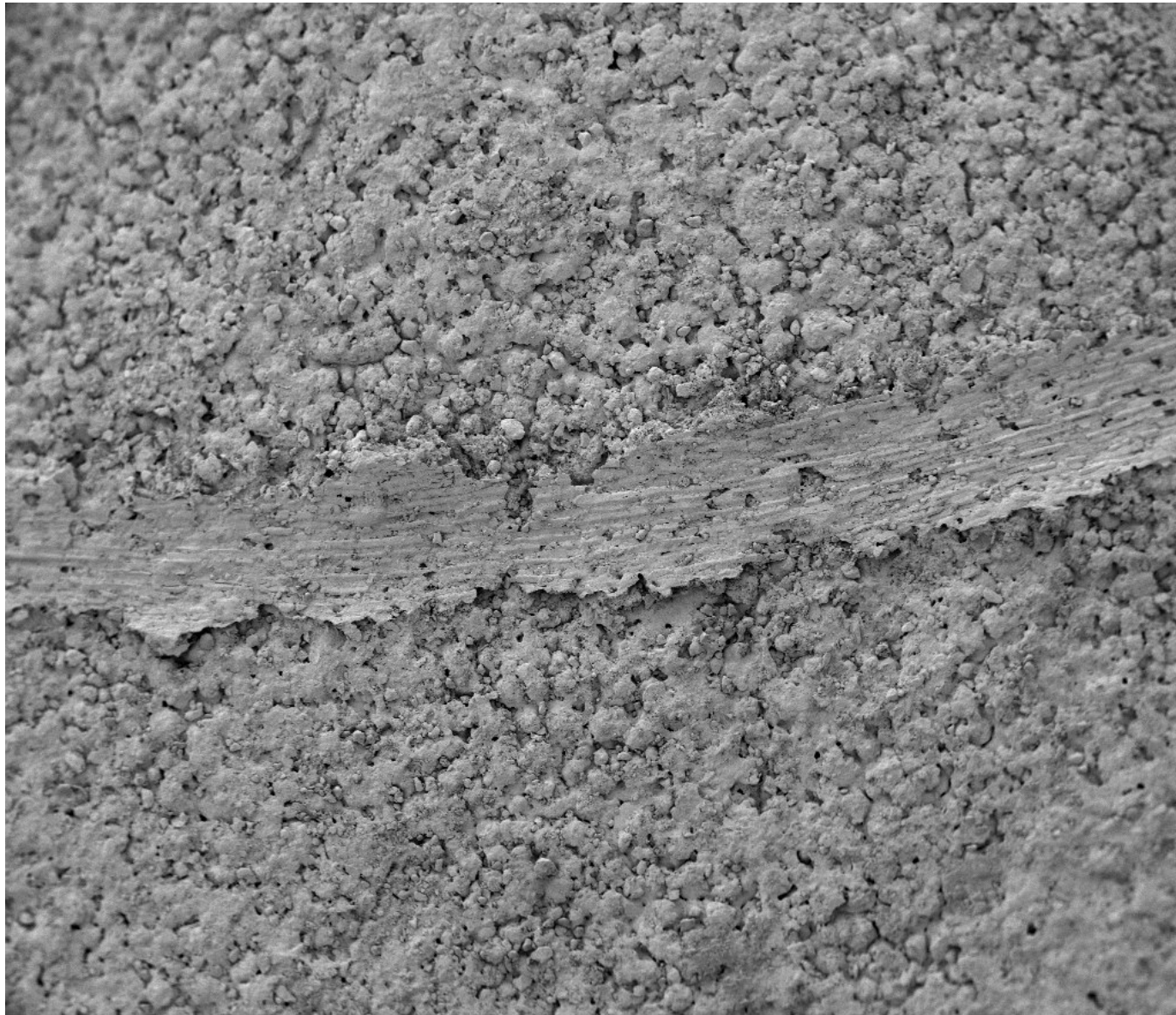
NANOIMAGING-LAB



00166803

————— 300 μm

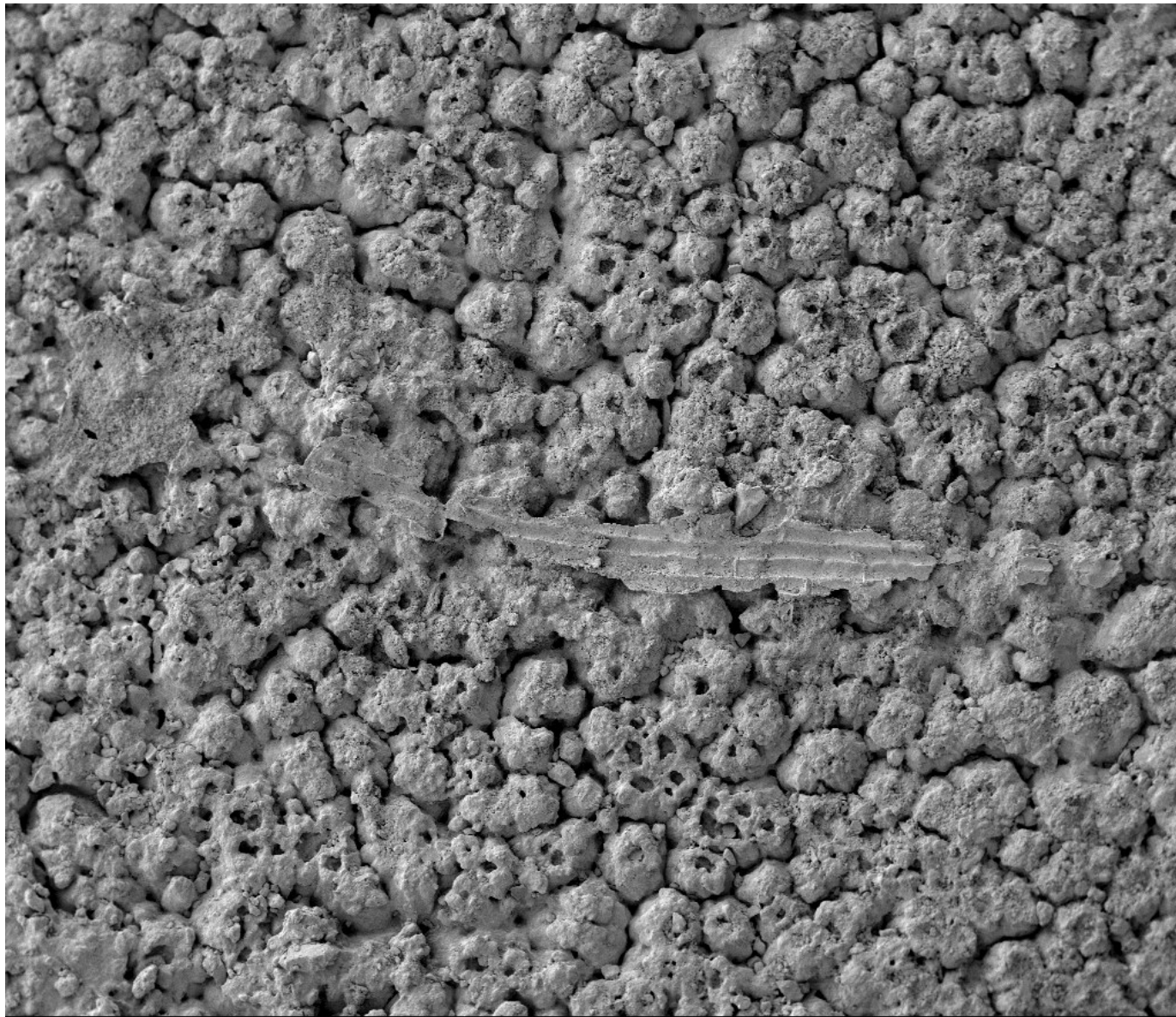
NANOIMAGING-LAB



00166821

————— 500 μm

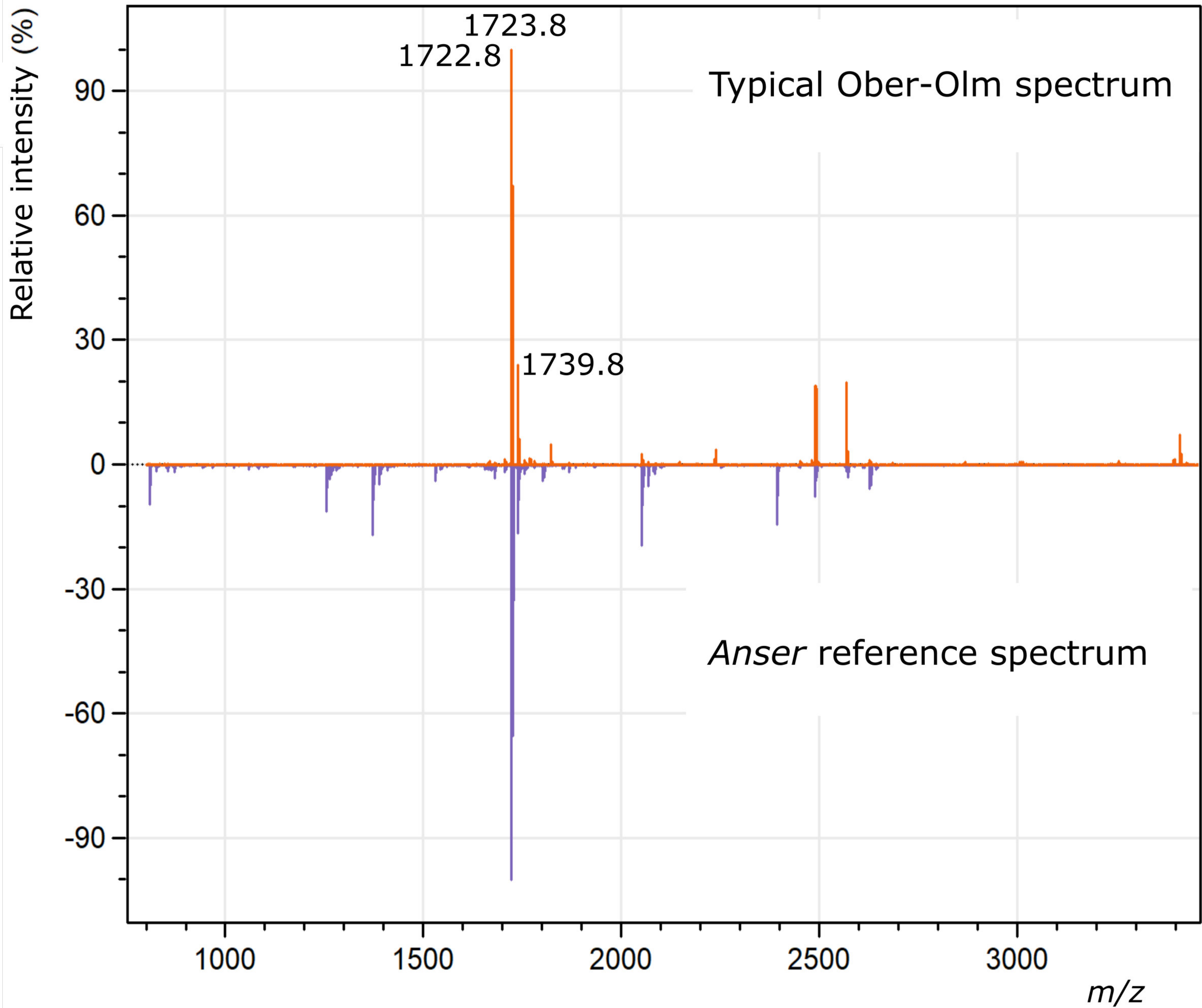
NANOIMAGING-LAB



00166837

————— 300 μm

NANOIMAGING-LAB



| | <i>Anser anser</i> | | <i>Gallus gallus f. dom.</i> | |
|---|--------------------|---------------------------------|------------------------------|--------------------------------|
| | n | mm ² | n | mm ² |
| surface uniformly corroded | 89 | 12002 | 75 | 4617 |
| mostly corroded with uncorroded zone(s) | 12 | 1530 | 9 | 686 |
| mostly uncorroded with corroded zone(s) | 8 | 1136 | 5 | 204 |
| surface uncorroded | 3 | 789 | 14 | 823 |
| Total | 112 | 15457 | 103 | 6330 |
| Degree of fragmentation | | 138.0 mm ² /fragment | | 61.5 mm ² /fragment |

Tab. 1: Modern hatched reference shells (*Anser anser* and *Gallus gallus f. d.*) quantified by number of fragments (n) and total shell fragment areas in square millimeters (mm²). Corrosion patterns and degree of fragmentation.

| | Sample I | | Sample II | | Sample III | | Sample IV | | Sample V | |
|---|--------------------------------|-----------------|--------------------------------|-----------------|--------------------------------|-----------------|--------------------------------|-----------------|---------------------|-----------------|
| | n | mm ² | n | mm ² | n | mm ² | n | mm ² | n | mm ² |
| surface uniformly corroded | 2 | 38 | 5 | 696 | 4 | 212 | 7 | 330 | | |
| mostly corroded with uncorroded zone(s) | 1 | 20 | 1 | 59 | 6 | 282 | 4 | 203 | | |
| mostly uncorroded with corroded zone(s) | 13 | 1424 | 12 | 924 | 14 | 1106 | 36 | 2920 | | |
| surface uncorroded | 80 | 6474 | 97 | 6578 | 81 | 4471 | 83 | 4222 | | |
| not assessable | 47 | 3341 | 7 | 1029 | 5 | 570 | 3 | 300 | | |
| Total | 143 | 11297 | 122 | 9286 | 110 | 6641 | 133 | 7975 | no eggshells | |
| Degree of fragmentation | 79.0 mm ² /fragment | | 76.1 mm ² /fragment | | 60.4 mm ² /fragment | | 60.0 mm ² /fragment | | | |

Tab. 2: Modern compost eggshells (*Gallus gallus f. d.*) quantified by number of fragments (n) and total shell fragment areas in square millimeters (mm²). Corrosion patterns and degree of fragmentation.

| | Sample I | Sample II | Sample III | Sample IV | Sample V |
|---------------------------------|-------------|-------------|-------------|-----------|-------------|
| Calcium carbonate (dolomite) | 21% (2%) | 17% (2%) | 17% (2%) | 8% | 20% (2%) |
| Loss on ignition | 42% | 35% | 20% | 33.5% | 3.5% |
| Phosphates | 6.9 c.u. | 4.7 c.u. | 6.1 c.u. | 5.6 c.u. | 4.3 c.u. |
| Humic substances | 1.5 c.u. | 1.3 c.u. | 1.3 c.u. | 1.1 c.u. | 0.2 c.u. |
| pH | 7.8 | 7.8 | 7.8 | 8.1 | 8.6 |

Tab. 3: Geochemical measurements of the compost sediments (<0.5 mm fraction).

| | assemblage 4 | | assemblage 5 | | assemblage 6 | | not assignable | |
|---|---------------------------------|-----------------|---------------------------------|-----------------|---------------------------------|-----------------|---------------------------------|-----------------|
| | n | mm ² | n | mm ² | n | mm ² | n | mm ² |
| surface uniformly corroded | 6 | 1121 | 3 | 361 | 1 | 48 | 0 | 0 |
| mostly corroded with uncorroded zone(s) | 17 | 5547 | 19 | 2460 | 2 | 213 | 1 | 79 |
| mostly uncorroded with corroded zone(s) | 26 | 2988 | 70 | 6612 | 53 | 5953 | 5 | 554 |
| surface uncorroded | 5 | 464 | 7 | 1310 | 16 | 1022 | 1 | 114 |
| not assessable | 3 | 480 | 4 | 463 | 0 | 0 | 0 | 0 |
| Total | 57 | 10600 | 103 | 11206 | 72 | 7236 | 7 | 747 |
| Degree of fragmentation | 186.0 mm ² /fragment | | 108.8 mm ² /fragment | | 100.5 mm ² /fragment | | 106.7 mm ² /fragment | |

Tab. 4: Archaeological eggshells (*Anser anser?*) quantified by number of fragments (n) and total shell fragment areas in square millimeters (mm²). Corrosion patterns and degree of fragmentation.

Figure captions

Fig. 1: Schematic drawing of an egg at an advanced stage of incubation (Figure by B. Sichert, based on a figure by A. L. Romanoff cited by Ridlen/Johnson 1964, 13 Fig. 9.).

Fig. 2: Modern hatched reference shell of *Anser anser* (Figure by O. Fischer and B. Sichert).

Fig. 3: Section through the compost pile and location of the samples. Sample V (former subsoil) contained no eggshells (Figure by B. Sichert).

Fig. 4: Burial 19 (Ober-Olm, Germany) (Figure by M. Vitucci and B. Sichert).

Fig. 5: Corrosion patterns on modern hatched reference shells, archaeological shells of burial 19 (Ober-Olm, Germany) and modern compost eggshells quantified by number of fragments (n) and total shell fragment areas in square millimeters (mm²). Above: absolute numbers/areas. Below: percentages (Figure by B. Sichert).

Fig. 6: Remains of organic shell membranes on compost eggshells (Figure by B. Sichert).

Fig. 7: Modern compost eggshell (*Gallus gallus f. d.*). Corroded mammillae and remains of the organic shell membrane (m) (Figure by E. Bieler and B. Sichert).

Fig. 8: Modern compost eggshell (*Gallus gallus f. d.*). Uniformly corroded shell (Figure by E. Bieler).

Fig. 9: Modern compost eggshell (*Gallus gallus f. d.*). Mostly corroded shell with uncorroded zone (bottom right) (Figure by O. Fischer).

Fig. 10: Stereomicroscopic image of an eggshell (*Anser anser?*) from burial 19 (Ober-Olm, Germany). Mostly corroded shell with two uncorroded zones (left side) (Figure by O. Fischer and B. Sichert).

Fig. 11: Archaeological eggshell (*Anser anser?*) from burial 19 (Ober-Olm, Germany). Uniformly corroded shell (Figure by E. Bieler).

Fig. 12: Archaeological eggshell (*Anser anser?*) from burial 19 (Ober-Olm, Germany). Corroded and uncorroded mammillae (Figure by E. Bieler).

Fig. 13: Archaeological eggshell (*Anser anser?*) from burial 19 (Ober-Olm, Germany). Zone of excessively flattened mammillae (lower half) (Figure by E. Bieler).

Fig. 14: Archaeological eggshell (*Anser anser?*) from burial 19 (Ober-Olm, Germany). Corrosive feature on external (convex) side (Figure by E. Bieler).

Fig. 15: Archaeological eggshell (*Anser anser?*) from burial 19 (Ober-Olm, Germany). Root groove and uncorroded shell (Figure by E. Bieler).

Fig. 16: Archaeological eggshell (*Anser anser?*) from burial 19 (Ober-Olm, Germany). Root groove and mostly corroded shell with uncorroded zones (Figure by E. Bieler).

Supplementary figure caption

Supplementary figure I: Typical MALDI-MS spectrum obtained on the eggshell fragments analysed from burial 19 (Ober-Olm, Germany) (top), compared with a reference spectrum obtained on a modern *Anser sp.* eggshell (bottom). Labelled peaks indicate Anseriformes markers (Figure by B. Demarchi).