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Looking beyond appearances: a multi-analytical approach on the prehistoric clay weights

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Abstract

In this paper we analyzed a batch of 64 clay weights from three archaeological sites located in Romania (Gumelniţa, Măgura-Jilava, and Sultana) that belong to Kodjadermen-Gumelniţa-Karanovo VI cultural complex (4600–3900 cal. BC). Our approach includes an interdisciplinary investigation based on technological analysis, experimental archaeology, and X-ray CT scans coupled with statistical analysis. This investigation has a high potential to reveal relevant information regarding the technological background (e.g., inclusion, voids, temper, etc.), manufacturing stages (e.g., modeling, shaping, kneading, etc.), or transformation processes (e.g., drying and firing vs. weight and size modification) in order to identify, explain and understand the *chaîne operatoire* for this type of artefacts. Moreover, correlation of the results with the experimental archaeology could offer an integrative interpretation about the material culture of past humans and its multiple meanings, but also critical information about the multiple dimensions of manufacture for these objects (e.g., time, effort, physical–chemical processes, etc.). The multi-analytical approach proposed here also includes a comparative study of technological aspects of these clay weights across the three archaeological sites investigated, as well as the experimental replicas.

Keywords: Southern Romania, Neolithic, Clay weights, X-ray CT scan, Experimental archaeology

Introduction

The study of material culture offers the potential to reveal essential information about past human life-style, technologies, economy, society, religion, and exchange networks. This is especially critical in the case of prehistoric communities for which there are no written sources (e.g., inscriptions, books, documents, etc.), but also makes it more challenging to interpret the use and social significance of ancient objects. Hence, the combination of systematic archaeological excavations, detailed recording of data in the field, and comprehensive, quantitative analyses of the artifacts/ecofacts, are necessary tools for the investigation and interpretation of the distant past.

Archaeological investigations of Neolithic communities have recovered a broad set of artifacts made from various raw materials reflecting the complexity of their lifeways. As many researchers have noticed over time, clay weights represent one of the most common types of archaeological findings within the Neolithic sites in Europe [1–3], which might indicate the presence of the warp weighted loom in this chrono-geographical setting [4, 5]. However, their study in the Balkans has been neglected, given the small number of papers that address this topic. Despite a large number of such artifacts discovered in Balkan Neolithic sites, the few published studies are primarily descriptive in nature. Technological and functional studies are lacking, which is why the present paper takes a multi-proxy approach to the study of clay weights.

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The main goal of the research we report here is to understand the complex aspects of clay weight manufacture (*chaîne operatoire*), as revealed through our multi-analytical approach, and how it integrates within the cultural variability of the Gumelnița people. Although the current study classifies these items into the functional classes, it focuses primarily on analyses of size, fabric, morphology, and techno-typological observations. These investigations of prehistoric objects are informed by the production of experimental replicas, which were analyzed in the same way as the prehistoric specimens. All results were statistically evaluated using multivariate test methods.

Our novel approach combines archaeological analyses with experimental replication studies, techno-functional analysis of the clay weights, and X-ray computed tomography (XCT) along with statistical analysis in order to decipher the manufacturing processes of these artifacts and their possible uses. While petrographic analysis would also be helpful, this was not possible because it requires invasive analysis that is not permitted on museum specimens.

Interdisciplinary investigation like the one we report here has the potential to reveal new information about past technologies of the clay weights; if correlated with other kind of data (e.g., archaeological context, chronology and use-wear traces), it could offer an integrative interpretation about past human material culture and its multiple meanings.

Materials and methods

Materials

The studied sample includes 64 clay weights from three archaeological sites—Gumelnița, Măgura-Jilava, and Sultana (Fig. 1). All three are tell-settlements located in southeastern Romania; they belong to

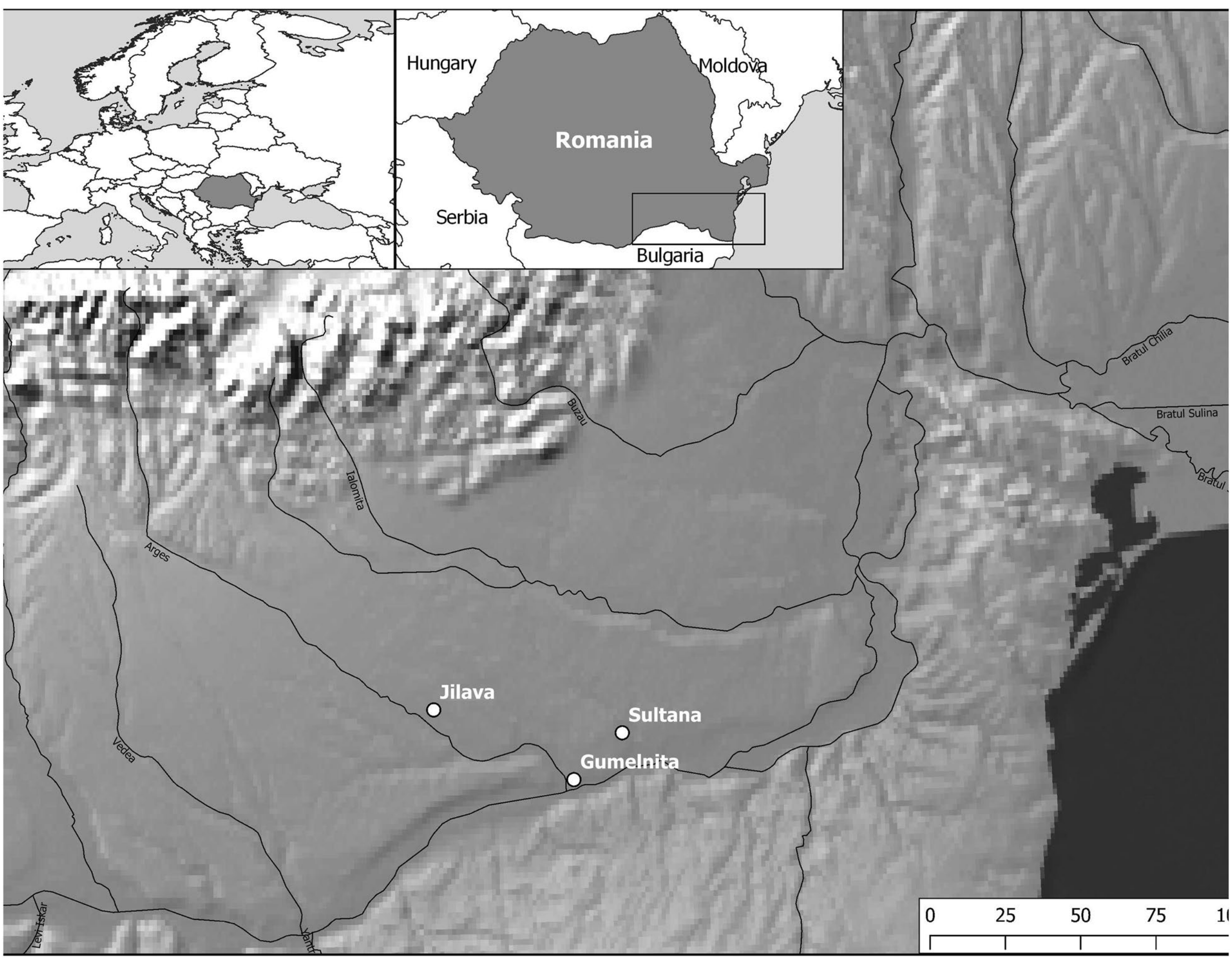

Fig. 1 Map of the sites' distribution

Kodjadermen-Gumelnița-Karanovo VI cultural complex (4600–3900 cal. BC) [6]. The items from Gumelnița and Măgura-Jilava lack detailed archaeological context, as they were excavated decades ago and they suffered poor post-excavation management [7–11]. Detailed contextual data are available only for the most recent excavations from the Sultana (the tell settlement from Malu Rosu point) [12]. The pieces included in this study are curated by three museums from Romania (Municipality Bucharest Museum, Lower Danube Museum in Calarași, and Gumelnița Civilization Museum in Oltenița).

Methodology

Archaeological study

The fabric analysis of the clay weights follows current ceramic material study procedures, including the paste groups, temper characteristics, and inclusion types [13–17]; for techno-typological observations we used studies that addressed that issue [1]; we also performed macroscopic observations on use-wear traces. All items were measured for weight, height, width, thickness and perforation diameter using a ruler and electronic calipers. For use-wear investigation we used a binocular magnifier, along with photos taken with a macro lens. Macroscopic examinations coupled with a binocular magnifier inspection were used to identify the inclusions in the paste and to classify into groups the analyzed items. All observations were introduced into a database that was later used for quantitative analyses.

Experimental approach

Considering that the archaeological record is limited, experimental archaeology can be used for obtaining data to test models, leading to a better understanding of past aspects [18]. Experimental archaeology can be a critical tool to reconstruct the techniques, procedures and processes involved in creating artifacts or structures [19, 20].

The experimental replication of the archaeological clay weights involved the methods and protocols developed by our team [21] in order to reconstruct the manufacturing process and associated technological components (e.g., gathering of raw materials, paste preparation, drying and firing methods). Data recording was made with standard registration forms, including the typological, metrical, and contextual information also recorded for archaeological artifacts, along with technical (the number of persons involved in the experiment, the quantity of raw material used, etc.), temporal (time required for the various stages of the experiment) and thermal elements (firing duration and temperatures) of the experimental manufacturing stages. For typo-technological aspects and measurements we use the same methods applied to the archaeological items, described above. The raw material gathering and manufacturing process of the experimental replicas was made with reproductions of prehistoric tools. Firing of the experimental clay weights was done with a Protherm Furnace model PLF 110/6, with an inner volume of 6.3 L, and capable of reaching a maximum temperature of 1100 °C. The oven is also equipped with data collection software that allowed us to record detailed temperature information throughout the entire process (Fig. 1). The raw materials we used in the process were weighted with a standard digital scale.

XCT investigations

During the last few decades the XCT method has been successfully applied in archaeological research [22–24]. Here, it was used to provide details about the internal structure of artifacts that cannot be otherwise discerned except through destructive analyses. The application of XCT proved to be an excellent non-invasive approach for the study of prehistoric clay artifacts, being especially relevant to investigate the internal structure and/or hidden details of unbroken/intact archaeological items (Figs 2a, b, 3a, b). The inner structure of an artifact can provide important insights about its manufacturing process or its function. This method allows detailed identification of artifact production procedures, clay fabric characteristics, the presence/absence and interpretation of several features of the inclusions and voids (form, frequency and size) regarding the inclusions and voids. In order to analyze the form of the inclusions we have taken as a model the inclusion roundness classes (angular, subangular, subrounded, rounded and well-rounded) and the categories of roundness for grains (high sphericity—very angular, angular, subrounded, rounded and well-rounded; low sphericity—very angular, angular, subrounded, rounded and well-rounded) [25]. The frequency was interpreted based on the inclusion density charts from the same publication. The visualization of the inclusions present in the internal structure of the clay weights was made possible by manipulating the contrast of the 3D images (Figs 2a, b, 3a, b). For each analyzed object, different degrees of transparency were used, which led to the clear distinction of inclusions which were subsequently measured with the help of a millimeter measurement scale added to the 3D images. For the classification of the voids shapes we have established three general categories (irregular and elongated form, straight and elongated form and ovoid or spherical form), and for the interpretation of their frequency, by extrapolation, we used the same density charts as in the case of the inclusions. The voids sizes were calculated based on the sliced XCT-scans with the help of the horizontal millimeter scale present in each image.

Although XCT-scan analysis is not a substitute for petrographic investigations, it is very useful and effective tool for identifying the detailed elements of the modeling techniques, the effort put into preparing the raw material and fabricating the product, and whether the inclusions in the paste are natural or deliberately added.

The XCT scans reported in this paper were performed with a Nikon XT H 225 device that contains a microfocus X-ray source (225 kV maximum voltage, 1 mA maximum current, focal spot size: 3 µm below 7 W and up to 225 µm at 225 W) that provides a conical X-ray beam, a Varian 2520 flat panel detector (127 µm pixel size; 1900×1516 active pixels), and an accurate 5 axes positioning system, which allows movements of the sample in the X, Y, and Z direction, as well as its rotation with 360° and tilting by $\pm 30°$. The average voxel size is roughly 1.5×10^5 µm^3. This equipment allows the inspection of relatively large volume objects with high image resolution and an ultrafast CT reconstruction. The X-ray tube working parameters were optimized for the tomography of clay artifacts, i.e. a tube voltage of 100 kV and a current intensity of 45 µA. Each item was scanned in its entirety in 360 steps, representing a full rotation of the object around its central axis. The acquisition time for a full tomographic scan was roughly 6 min, while the image reconstruction performed with VGStudio Max 3.0 software18 took several minutes.

The XCT image analysis was carried out as visual inspection of thereconstructed images. This approach was followed because VGStudio Max 3.0 software is a general purpose tool for 3D reconstruction. The analyzed voids are the result of a visual inspection of the slices, and therefore not all the identified voids are perpendicularly oriented with respect to the orthoview planes.

For the interpretation of the imaging data obtained on the investigated artifacts, we followed the recent recommendations for interpreting X-ray images [26], coupled with our previous experience in the field [21, 27].

The XCT equipment is located at Horia Hulubei National Institute for Nuclear Physics and Engineering (Romania), and all the investigations in this article were done in this laboratory. Considering the preservation state of some items, only for 56 archaeological clay weights was possible to apply XCT investigation.

Statistical analysis

We carried out all statistical tests and produced all graphs with the *R* and *RStudio* statistical environment [28, 29]. We have employed univariate and multivariate statistics, as shown in the relevant section below.

Archaeological data set

The clay weights studied in this paper exhibited different shapes and sizes (Table 1, Additional file 1: Table S1, Additional file 2: Table S2, Additional file 3: Table S8, Additional file 4: Table S9). With a total of 41 pieces, the ovoid clay weights are the most common shape in the sample, followed by those of pyramidal shape (16). In addition to the two dominant typological categories (which add up to 57 pieces), several other types of clay weights shapes such as triangular (1), ring (1), prismatic (3) and conical (2) were identified (Table 1).

The weights of the 64 clay weights fall between 87 and 567 g, except for one specimen weighing 1024 g (Additional file 2: Table S2, Additional file 3: Table S8). They vary in thickness from 1.2 to 7.0 cm, in height from 7.8 to 15.0 cm, and in width from 3.4 to 14.8 cm. In terms of perforation dimension, the clay weights have circular holes with diameters between 0.3 and 2.9 cm (Additional file 3: Table S8).

Sometimes an object can perform more than one function. Over time, archaeologists assigned clay weights to two functional categories: loom weights and fishing net weights. As there is always the possibility that an object can perform more than one function, the clay weights were assigned to several functional categories over time, but mainly into two distinct groups: loom weights and fishing net weights. Weights were classified into these two functional classes by researchers according to several factors, the most notable being the positioning of the gripping hole and the wear traces [30]. In the past, the function of clay weights was often misinterpreted, the initial idea being that all served as accessories for fishing nets. This theory was subsequently refuted by details such as the position of the grooves of usage, shape and weight [3].

Within the studied assemblage, 63 specimens have the hole positioned in the upper part of the body (except for one piece that has the hole positioned in the center). Moreover, the vast majority of our clay weights show

Table 1 Clay weights data set typological composition across sites

Archaeological site	Pieces	Ovoid	Pyramidal	Prismatic	Conical	Triangular	Discoid
Gumelnița	21	9	12	0	0	0	0
Sultana	36	27	4	2	2	1	0
Măgura-Jilava	7	5	0	1	0	0	1

traces of use in the form of cord marks located in the upper area of the holes, indicating that they were suspended in a vertical position when in use. Some of the pieces have oblique thread marks that could indicate their utilization either as weights in clusters or for fishing nets. Most of these items show visible wear marks such as thread traces, in many cases these imprints being very distinct due to their depth, indicating a long-term use of them. For such marks to be visible on the surface of the fired clay items an intensive use is required [4].

As already mentioned, all clay weights were discovered in tell settlements. Most of the pieces were discovered in typical archaeological features (e.g., buildings, pits, etc.). An example in this respect is the L2 dwelling from Sultana that was identified on the southwestern edge of the tell settlement. This burned dwelling contained over 30 clay weights grouped in its southeastern limit [31], and 24 of them (22 ovoid, 1 prismatic, 1 triangular) were included in this study.

Results

Technological analysis

Most of the investigated clay weights (43 items) were complete, and 21 were discovered in fragmentary state. Macroscopic inspection of this sample allowed us to identify several technological/fabric features, such as paste quality, the kind of temper added to the paste, natural inclusions, voids, and surface treatment after their modeling.

This preliminary examination coupled with a binocular magnifier inspection, facilitated the definition of three categories of paste based on the texture of the material: fine, semi-fine, and coarse. Objects made from fine and semi-fine paste are the most common (31 and 27, respectively), while only a few were manufactured from coarse (5) paste (Table 2; Additional file 5: Table S3).

The most common anthropic inclusions (tempers) noticed in the paste composition are grog (crushed shards) (14), chaff (10), and crushed shells (10). Natural inclusions identified in the paste composition are mostly sand (alone or combined with other components) (17), pebbles (4) and carbonate concretions, as well as, lime-scale deposition on the items surface, depending on the environmental condition and the sediment type in which they were preserved [32].

Table 2 Type of paste for clay weights across sites

Paste	Gumelniţa	Sultana	Măgura-Jilava	Total
Fine	12	21	0	31
Semifine	8	11	6	27
Coarse	1	4	1	6

In 56 cases surface treatment was achieved through smoothing. Only 8 clay weights were polished; in case of one specimen surface treatment remained unidentified due to the very poor conservation status and severe lime-scale deposits (Additional file 6: Table S4). More than half of the samples (37) does not have decorated surfaces. Of the decorated weights, (23) display a single type of decoration either as incisions (15) or as impressions (8) (Additional file 7: Table S5). The remaining three specimens display combined decoration, such as incisions–impressions (2) and incisions–perforations (1). It is worth mentioning that the 26 decorated clay weights show a series of incised geometric and linear motifs.

We noticed several aspects of firing quality based on the colors of the analyzed items. One notable feature is that most of the clay weights were intensively fired, the major color being dark-brown (28), followed closely by brick-red (26), while the rarest color is a light shade of cream (6), which is likely to indicate a low firing temperature. For five pieces color could not be determined due to severe lime-scale deposits.

We compared the weights from different sites to detect any potential differences between them, in terms of shape, paste, temper, surface treatment and decoration. Most of the items were discovered at Sultana (36), and they can be divided into five typological categories according to their shape: ovoid (27), pyramidal (4), conical (2), prismatic (2) and triangular (1) (Tables 1, 2, Additional file 5: Table S3, Additional file 6: Table S4). The most frequent paste category identified for them is the fine paste (19). The rest of the items were made from semi-fine (13) and coarse (4) paste. Smoothing is the best represented surface treatment displayed by these pieces. 78% of the clay weights from Sultana are undecorated. The remaining eight decorated weights exhibit a range of geometric and linear techniques in the bottom area, and in two cases also occurring in the middle or upper area of the body. The predominant patterns are incisions and impressions. Even though detailed description of all the decorated specimens is not intended here, we note one clay weight of ovoid shape that bears a geometric motif consisting of an incised figure similar to an hourglass. In the lower part of the "hourglass" are 12 impressions (Additional file 7: Table S5, Additional file 8: Table S6).

As opposed to Sultana, the typological spectrum from Gumelniţa site is dominated by two shapes only: pyramidal (12) and ovoid (9) (Tables 1, 2, Additional file 5: Table S3, Additional file 6: Table S4). For 14 items, the surface treatment was done by smoothing, the other seven specimens having polished surfaces. It is important to note that 12 of the clay weights from this site are made of fine paste, while eight items display semi-fine paste texture, and only one can be attributed to the coarse paste class. An interesting aspect regarding the clay weights from Gumelnița is that most of them (17) are decorated with incisions and impressions, whereas perforations occur only in one case, and the decorative motifs are geometric and linear. With respect to decoration positioning, a preference was given to the median and bottom areas of the clay weights; for almost a half (10) clay weights, the decorations are found on the base, as one or more rows of impressions and incisions (intersecting one another, occasionally) (Additional file 7: Table S5, Additional file 8: Table S6, Additional file 9: Table S7). While all clay weights from Gumelnița are decorated, three of them are notable for their similar decorative motifs. Each of them has triangle shaped decorations positioned in the bottom (2) and middle (1) part of the item, with uneven sides and the tip leading to the base.

Finally, the seven clay weights from Măgura-Jilava site show a typology dominated by ovoid shapes (5), follow by prismatic (1) and discoid (1) shapes. Only one specimen is made from a coarse-paste, and just one other treated by polishing (Additional file 5: Table S3, Additional file 6: Table S4, Additional file 7: Table S5, Additional file 8: Table S6, Additional file 9: Table S7). None of the seven clay weights feature any decorations (Tables 1, 2; Additional file 5: Table S3, Additional file 6: Table S4, Additional file 7: Table S5, Additional file 8: Table S6, Additional file 9: Table S7).

Experimental study

The main goal of the experimental study was to reconstruct stages in the clay weights manufacturing process. Through this method, our intention was to systematically identify all the procedures used to transform the raw material into finished items. While more than 40 experimental clay weights were manufactured by our team between 2012 and 2018, only five pieces were selected for the current paper in order to illustrate how the past people made these items. The reason for this limited selection was that the replicated samples were made by different people using a range of preparation and finishing methods, very well recorded in the lab, and reflecting a variety of the manufacturing procedures. This controlled variation used in our experiments could permit better insights about similarities and differences between assemblages analyzed from the three sites. Details of this replication study are described below.

The first stage of the experiment consisted in collecting clay from nearby Sultana site. This source, conventionally called source no. 8, contains a raw material similar to that used by the Eneolithic inhabitants of the tell settlement according to preliminary laboratory analyzes carried out on local clay samples and several archaeological ceramic fragments. While clay was collected, various other raw materials were also gathered, including reed strains, bones, and stones with a smooth surface, to be used as tools during the technological process.

The second stage of the experiment consisted of preparing the paste, involving several steps to prepare it for modeling. The first step involved kneading by one individual for 1:25 h. Then, the clay paste was cleaned of impurities (mainly naturally occurring calcium carbonates) to avoid potential difficulties during the modeling and firing. As mentioned earlier, the use of grog as temper agent is common among the Eneolithic communities, especially at Sultana. This is most likely for practical reasons, due to the effects that grog have on clay behavior during modeling (helping to effectively bind clay), drying (reducing the risk of cracks), and transformation during firing (increasing the resistance to thermal shock) [14, 33]. Hence, the paste was mixed with grog for most replicas, the volume occupied by the temper generally being around 10–15%. The temper was obtained through the effort of two individuals, over 15 min, who crushed the ceramic shards with stones and grinders, collected during the first phase of the experiment. Generally, every individual mixed his/her piece of clay with crushed shards (grog) within 1 min.

Modeling and shaping of the items represented next stage of the experiment. Modeling each clay weight was carried out by a single male or female. Each weight was modeled by hand from a single piece of clay, gradually pressing the clay of ideal plasticity until the desired shape was obtained. The suspension holes where pierced with reed sections immediately after the modeling was completed, when the clay was still soft. In terms of working time, this manufacturing phase that includes only items shaping was completed within 25–32 min, the differences in working time being influenced by the objects size and the skill and the experience of each experimenter. Morphologically, the experimental replicas obtained could be divided into three types: ovoid (3), pyramidal (1) and conical (1). Four of these clay weights have temper (e.g., grog) in their paste composition (see Additional file 10: Table S13).

After their modeling and shaping, the clay weights where dried for 2 days in an indoor environment (laboratory) at a constant average temperature of 25 °C.

The fifth stage of the experiment was the surface treatment. The surfaces of four replica clay weights were polished with river stones or shells belonging to the *Unio* species. The shortest surface treatment took 11 min to complete, whereas the longest polishing took 31 min

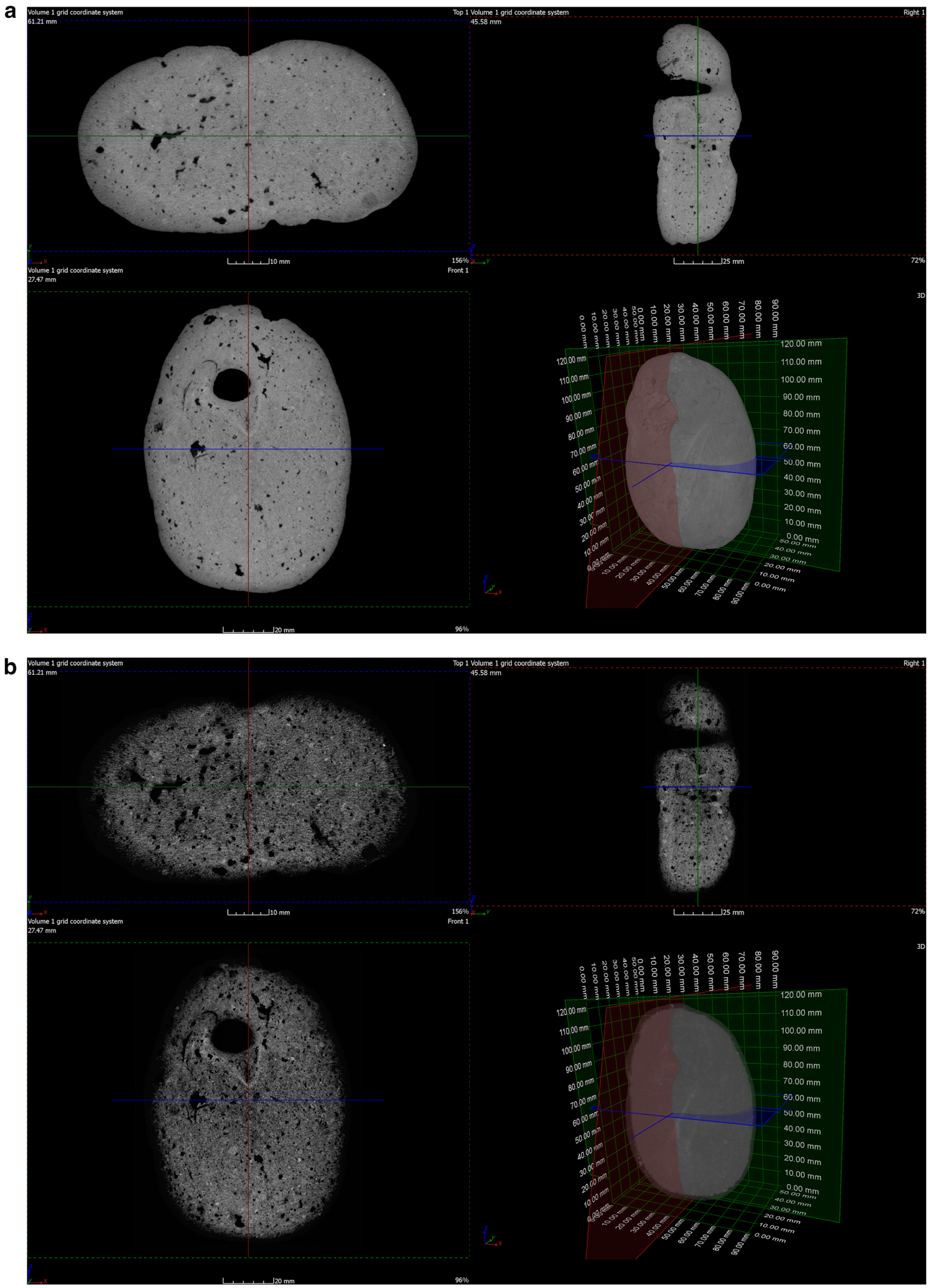

Fig. 2 Archaeological clay weight from Sultana. XCT-scans with different degrees of contrast and transparency: **a** low transparency and weak contrast; **b** high transparency and strong contrast

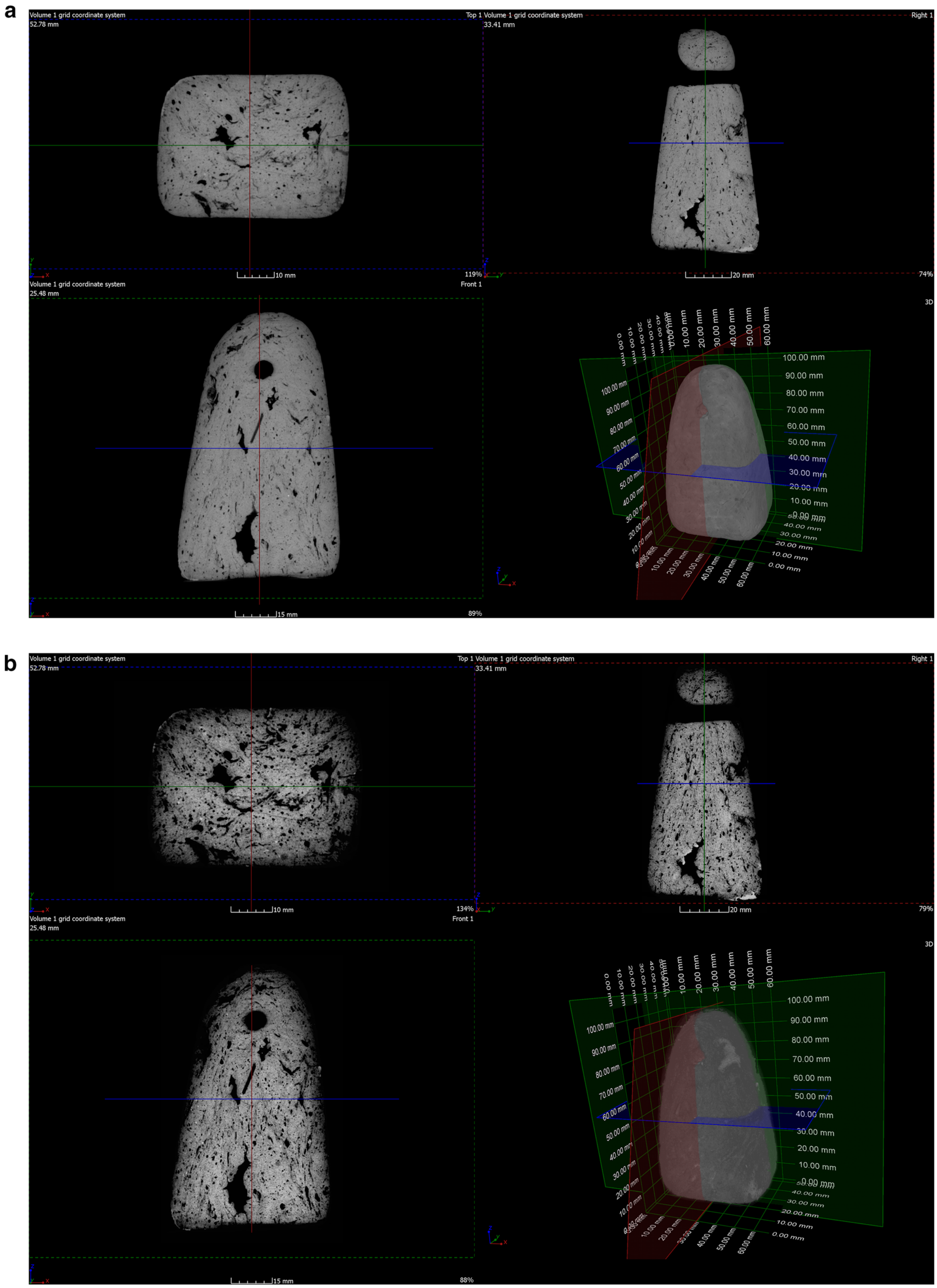

Fig. 3 Archaeological clay weight from Sultana. XCT-scans with different degrees of contrast and transparency: **a** low transparency and weak contrast; **b** high transparency and strong contrast

to complete. The polishing led to a slight weight loss (because of abrasion) averaging 6 g per piece.

After another 5 days of drying completed, the clay weights were fired in an oxidizing atmosphere, for the last stage of the experiment. This kind of firing was selected because all archaeological clay weights investigated display evidence of oxidized firing. The firing process was set to reach 700 °C within 2 h, and then maintained at the same level for an additional 1 h and 10 mins (Additional file 11: Figure S1). At the end of the firing, the temperature was dropped gradually to 100 °C, over 2 h (Additional file 11: Figure S1), at which time the firing was stopped and the clay weights were left inside the kiln for a slow natural cooling. The total firing time lasted 5 h and 10 mins, while the cooling time lasted for 16:50. The increase and the subsequent gradual decrease in temperature minimized the risk of damage to the clay weights due to thermal shock. As a result of this laboratory experiment which allowed us to precisely configure the desired parameters, all the experimental clay weights displayed a reddish color evenly distributed across their entire surface (see Tables 3, 4, 5).

For all experimental replicas, technical, time duration, temperature and firing characteristics were recorded. Monitoring the specimens during the technological sequences we were able to identify size and weight changes during drying and firing processes. The transformations in size and weight that the clay weights

Table 3 Experimental clay weights sample manufacturing characteristic and selected archaeological sample by shape

Archaeological clay weights			Experimental clay weights						
No.	Inventory number	Shape	Type of temper	Temper quantity (g)	Modeling time (m)	Drying time (days)	Type of treatment	Time of treatment (m)	Tool type
1	12/175,000	Pyramidal	Grog	38	25	5	Polishing	11	River stone
2	64/176,068	Ovoid	Grog	50	32	5	Polishing	11	River stone
3	174,990	Conical	Grog	60	27	5	Polishing	24	Union shell
4	N/A	Ovoid	N/A	N/A	25	6	Polishing	31	River stone
5	N/A	Ovoid	Grog	60	29	5	N/A	N/A	N/A

Table 4 Experimental clay weights thermic treatment characteristics against selected archaeological sample by shape

Archaeological clay weights			Experimental clay weights				
No.	Inventory number	Shape	Firing type	Firing installation	Firing time	Maximum temperature (°C)	Cooling time
1	12/175,000	Pyramidal	Oxidative	Lab. oven	5 h 10 m	700	16 h 50 m
2	64/176,068	Ovoid	Oxidative	Lab. oven	5 h 10 m	700	16 h 50 m
3	174,990	Conical	Oxidative	Lab. oven	5 h 10 m	700	16 h 50 m
4	N/A	Ovoid	Oxidative	Lab. oven	5 h 10 m	700	18 h
5	N/A	Ovoid	Oxidative	Lab. oven	5 h 10 m	700	16 h 50 m

Table 5 Experimental clay weights sample dimensional data before and after thermic treatment

Archaeological clay weights			Experimental clay weights					
			Dimensions H/W/T/D (diameter) in cm			Weight		
No.	Inventory number	Shape	After modeling	After drying	After firing	After modeling (g)	After drying (g)	After firing (g)
1	12/175000	Pyramidal	10/6.6/5.4	9.8/6.2/5	9.8/6.2/5	381	310	289
2	64/176068	Ovoid	11.6/7.9/4.1	11.4/7.5/3.8	11.4/7.5/3.8	501	409	377
3	174990	Conical	7.2/9.6/4.4	6.8/9.3/4.1	6.8/9.3/4.1	393	315	297
4	N/A	Ovoid	12/7.5/4.9	11.4/7.3/4.7	11.4/7.3/4.7	601	478	438
5	N/A	Ovoid	12.6/8/4.5	12.3/7.7/4.3	12.3/7.7/4.2	608	495	460

experienced during the experimental protocol are worth pointing out. The drying process affected both the size dimensions and the weights of the objects, while the changes recorded after the burning process were obvious only for weight (Table 5).

The most obvious changes drying and firing process that affected the dimensional variables during the drying process were for height (especially so for 3 items lacking temper). Clay weights with grog temper lost 2–4 mm in height, while the height of those without temper decreased by 6 mm. Changes were similar for all 5 experimental objects for the other dimensional variables, their sizes widths decreasing by 2–4 mm (Table 5). Once the experimental firing process stopped, the objects did not change further in size. The loss in weight experienced by the experimental clay weights was greater than size reduction and identified during both drying and firing: a loss of 17.1–20.5% during drying (71–123 g) and 6.8–8.4% after firing (21–47 g) (Table 5). In sum, from the beginning of the drying process and until the end of the firing the objects decreased by 23.8–27.2% in weight.

Imaging investigations

The XCT analysis involved scanning the archaeological clay weights, as well as the experimental replicas. We aimed at recording detailed information about how the clay weights were manufactured and paste composition. Imaging investigations were also performed on the experimental replicas in order to understand the similarities and differences between the archaeological finds and the experimental items manufactured under controlled conditions and with all production sequences recorded. That permitted better interpretation of the imaging data and their relationship with the structure and composition of the analyzed items. These data may become a useful reference index that can be used for future archaeological artifacts where such information is missing.

Considering the potential of the imaging investigations to answer different questions regarding pottery technology [26, 34, 35], we aimed to identify the following aspects: (1) characteristics of clay fabrics; (2)primary forming techniques; (3) artefact cracks, faults of fissures (for the original artefacts).

The results of the XCT analysis of the archaeological items are provided in Additional file 12: Table S10, Additional file 13: Table S11, Additional file 14: Table S12, Additional file 10: Table S13. The experimental clay weights also were microscopically analyzed through XCT-scan (Additional file 10: Table S13 for more images and XCT-scans of the data). This investigation helped us obtain a number of observations about the qualitative differences between the archaeological and experimental clay weights, based on the degree clay compaction.

Statistical analysis

As stated earlier in the paper, the main goal of this work was the understanding of the complex aspect related to the clay weights manufacture, as revealed from the various characteristics that we studied, and how we can relate that to the general cultural variability within Gumelnița culture.

To accomplish this goal, we performed an inter- and intra- site comparison, in order to understand the co-variation of the techno-typological characteristics of the clay weights under scrutiny here. A quantitative analysis was carried out, for the most informative characteristics involved in the process of manufacturing the clay weights, using *R* and the Integrated Development Environment (IDE) *RStudio* (Additional file 15 for the codes in R). We performed both univariate (e.g., Fisher's exact test, Kruskal–Wallis and Wilcoxon multiple pairwise test) and multivariate statistics (Model-based cluster analysis), which are widely used in social sciences, archaeology included, and relevant to the kind and size of the sample under investigation in our paper [36–38].

One of the very important typo-technological features we studied are the clay weights paste type and shape across sites (Fig. 4a, Tables 1, 2), (see also Additional file 5: Table S3, Additional file 6: Table S4, for details). We opted out to use Fisher exact test of independence in order to test whether or not they both vary independently each irrespective of sites. Fisher's test is suitable for small samples like ours, where Chi square tests requirements are not fulfilled [36]. In *R* the Fisher Exact Test has been extended to work with larger tables, provided that one does not obtain too large frequencies [39].

The Fisher's exact is very significant ($p=0.001$) in terms of clay weights paste type, and right at significance limit ($p=0.05$) for shape. This means that there are significant differences between sites relative to these features of clay weights manufacture. More specifically (see Fig. 4a) most of the artifacts from Sultana and Măgura-Jilava are ovoid in shape and predominantly made from fine and semi-fine paste, whereas at Gumelnița, although the majority of the artifacts are also made from fine and semi-fine paste, there are more pyramidal shaped ones, closely followed by the ovoid ones. It is important to note the fact that most of the items from the sites discussed here are predominantly made from fine and semi-fine paste. We also note also that results from Măgura-Jilava should be carefully considered because of the very small sample numbers.

Equally interesting results have been obtained for shape and surface treatment variation across sites. Here as well, Fisher's exact test of independence showed significant differences among sites, in terms of how shape and clay weights surface treatment covary across sites ($p=0.002$) (Fig. 4b). Again, the most obvious differences are between Gumelnița and Sultana. At Gumelnița the items are

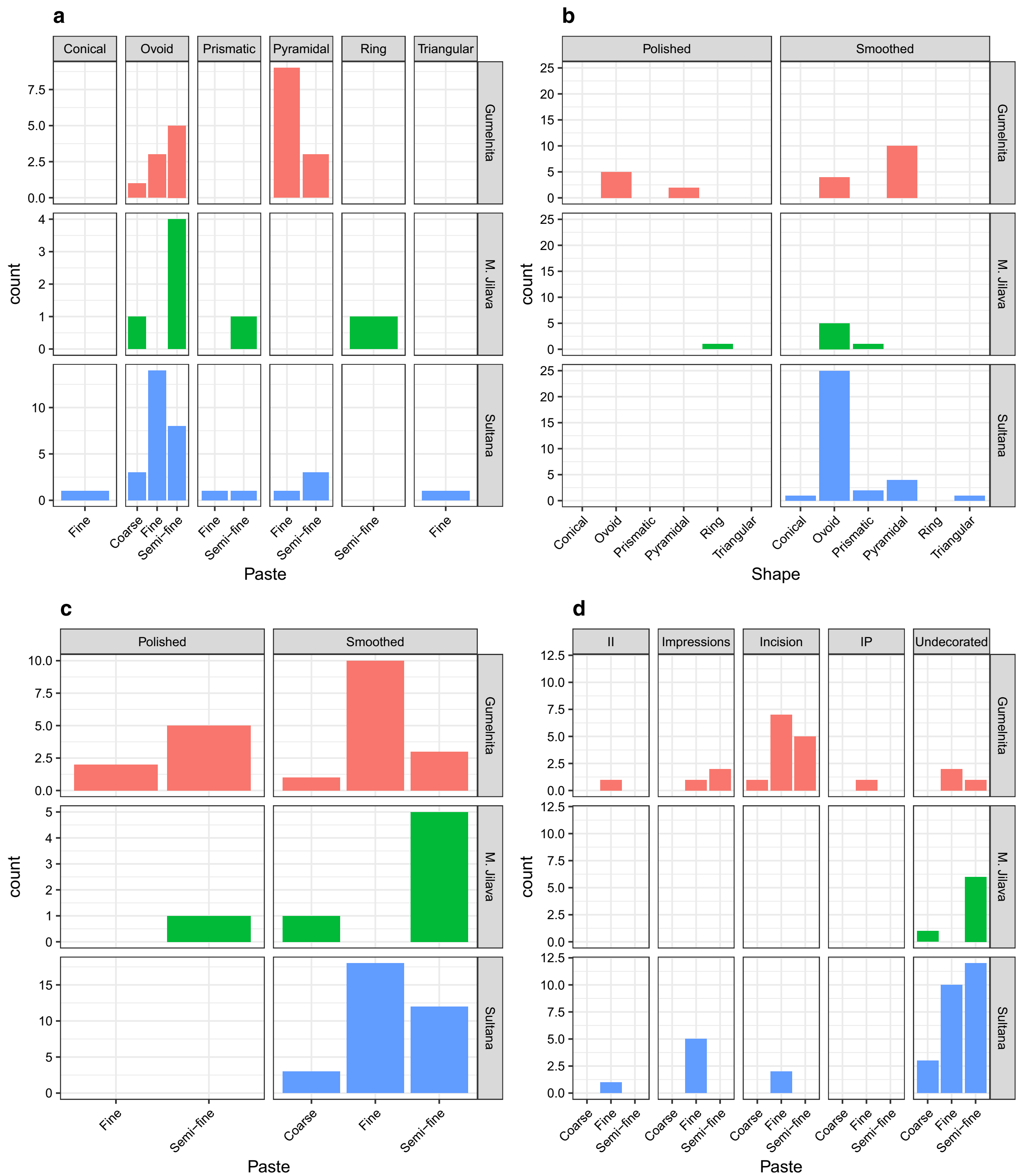

Fig. 4 Clay weights data set techno-typological characteristics variation across sites: **a** paste and shape variation; **b** shape and surface treatment variation; **c** paste and surface treatment variation; **d** paste and decoration variation (II: Incision–Impression; IP: Incision–Perforation

smoothed and polished, with the pyramidal mostly smoothed compared to the ovoid, while at Sultana, most of the clay weights are ovoid, and smoothed. The other shape types were less frequent and less often smoothed.

The same significant results are seen when paste and surface treatment are considered across sites, and the same differences occur between Sultana and Gumelnița (Fig. 4c) ($p=0.02$). Polished fine and semi-fine paste is completely absent from Sultana sample. Măgura-Jilava is consistent with the pattern observed at Sultana, but we suggest careful consideration of this small ample, as stated above.

Some clay weights in the studied data set were decorated and we compared this attribute with paste and across sites, as with the other attributes above. Here too, Fisher's test was significant ($p<0.001$). The majority of artifacts at Sultana are undecorated irrespective of paste type, and completely undecorated at Măgura-Jilava (Fig. 4d). On the other hand, all clay weights recovered from Gumelnița are decorated, with the incised decoration style being dominant, and only one item made from coarse grained being decorated.

Clay weights size variation across sites is an important feature in the manufacturing process of those artifacts, and relevant to our study research goals. Therefore, we performed an evaluation of the metrical data (e.g., thickness, height, width, hole diameter and weight) across sites. Shapiro–Wilk and Levene tests for normality and homogeneity testing (Table 6) suggest that a non-parametric test, such as Kruskal–Wallis, is well suited for our study [36, 37]. Hence, we used the Kruskal–Wallis test to compare these variables across sites (Table 6). Additionally, a pair-wise test was performed (Wilcoxon, pair-wise method), in order to assess the variation of these variables not only for the entire data set as whole, but also between sites.

The Kruskal–Wallis test for clay weights thickness by site is not statistically significant either across all sites ($H(2)=3$, $p=0.2$) nor between site pairs (Gumelnița and Măgura-Jilava, $p=0.85$, Gumelnița and Sultana, $p=0.14$, Măgura-Jilava and Sultana, $p=0.26$) (see Fig. 5a).

Clay weight height variation across sites is statistically significant at the entire data set level (Fig. 5b) ($H(2)=8$, $p=0.02$), but the pair tests revealed some particular results. There is no significant difference between Gumelnița and Sultana ($p=0.85$), however, the differences in height are significant between Gumelnița and Măgura-Jilava ($p=0.002$), and Măgura-Jilava and Sultana ($p=0.02$).

The differences in widths of clay weights across sites are highly significant at the whole data set level ($H(2)=20$, $p<0.001$) (Fig. 5c), just as they are for site pairs (Gumelnița and Măgura-Jilava, $p=0.04$; Gumelnița and Sultana, $p<0.001$; Măgura-Jilava and Sultana, $p=0.04$).

On the other hand, there are no significant differences in hole diameter across all sites, at the data set level (Fig. 5d) ($H(2)=2$, $p=0.4$), nor pair-wise between sites (Gumelnița and Măgura-Jilava, $p=0.124$; Gumelnița and Sultana, $p=0.69$; Măgura-Jilava and Sultana, $p=0.315$).

Last but not least, there is some interesting variability when the weight of the studied clay weights was considered. As such, Kruskal–Wallis test revealed quite significant differences across sites overall (Fig. 5e) ($H(2)=10$, $p=0.008$), but there is also variation in results, on a pair-wise level between sites. As such, no significant difference was found between Gumelnița and Sultana ($p=0.3$), but significant differences do exist between both Gumelnița and Măgura-Jilava ($p=0.02$) and Măgura-Jilava and Sultana ($p=0.002$).

The univariate statistics are useful to help reveal similarities and differences of the various technological choices that prehistoric people selected in the clay weights manufacturing process. However, we also need to understand whether the technology related variables (inclusions frequency and size, voids frequency and size) recorded through XCT-scan, taken as a whole, cluster into different groups that might correspond to sites membership. This is important in our endeavor to understand inter- and intra-site clay weights technological variability, that can be later connected to future use-wear and experimental studies regarding the functionality (e.g., loom weights, fish net weights, etc.) of the items involved in this study, and further applied to other data sets.

To achieve this, we employed a multivariate statistics method (i.e., cluster analysis), to the set of technological variables recorded: Inclusions frequency (percentages), Inclusions sizes (in mm), Voids frequency (percentages) and voids sizes (mm), which are available for 50 items in our analytical batch. Although not without issues, just like with any other quantitative method, cluster analysis is widely and efficiently used in archaeology in general [36–38], as well as for studying clay weights in other contexts [40, 41]. We opted for a Model-based cluster analysis, which we detail below [42–44]. As the details pertaining to this clustering method have been laid out in the works cited here, we only point out the main ideas behind it.

Table 6 Normality (Shapiro–Wilk) and homogeneity (Levene) tests for clay weights sizes distribution across sites

Category	Sh-W	Levene
Thickness-Site	W = 0.9, p = 0.01	F = 2.6, p = 0.08
Height-Site	W = 1, p = 0.6	F = 3.68, p = 0.03
Width-Site	W = 0.9, p < 0.001	F = 2.12, p = 0.13
Hole diameter-Site	W = 0.8, p < 0.001	F = 1.86, p = 0.17
Weight-Site	W = 0.9, p < 0.001	F = 0.79, p = 0.46

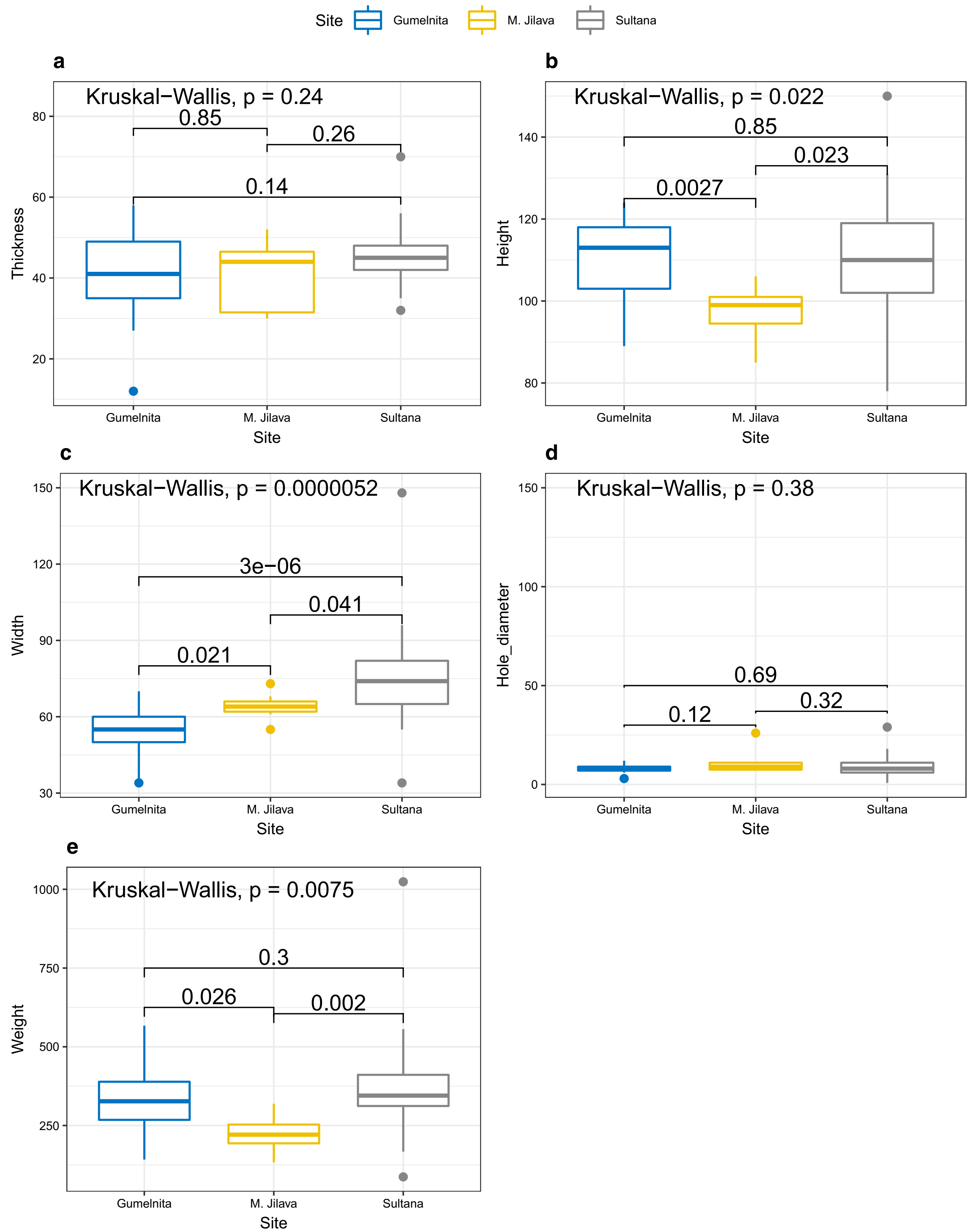

Fig. 5 Clay weights data set dimensional characteristics comparisons across sites: **a** thickness comparison across sites; **b** height comparison across sites; **c** width comparison across sites; **d** hole diameter comparison across sites; **e** weight comparison across sites. Kruskal–Wallis test significance shown on each graph

As opposed to other clustering methods (e.g., k-means, hierarchical clustering), which are heuristic and not based on formal models, *model-based clustering* (MBC, henceforth), considers the data as coming from a mixture of two or more clusters [42, 43]. MBC differs from more traditional methods in its definition of fuzzy assignments, which means that each point in a framework has the probability to belong to each cluster. In this method, therefore, data is considered as coming from a mixture of density [42, 43].

The Expectation–Maximization algorithm that is initiated by hierarchical model-based clustering is used for estimating the model parameters. The clusters are centered at the means, having the increased density for points close to the mean. The covariance matrix $\sum_k$ determines the geometric features of each cluster: shape, volume, orientation. In *R* the package *mclust* offers different possible parameterizations of $\sum_k$ [43, 44]. The available model options in *mclust* package are identified through the use of various acronyms, including: EII, VII, EEI, VEI, VVI, EEE, EEV, VEV, and VVV. The first identifier refers to volume, the second to shape and the third to orientation. *E* stands for "equal", *V* for "variable" and *I* for "coordinate axes".

In *R* all models are fit in *mclust* package using the maximum likelihood to fit all the available models, with different covariance matrix parametrization, for a range of components (*k*). The Bayesian information criterion (BIC henceforth) is used to select the best model, a large BIC indicating a strong evidence for the corresponding model [43, 44].

The next step is to compute the model-based clustering. This is done in *R* with the *mclust* package (see Additional file 16 for the *R* code details, including data preparation and model run). For our data set the MBC selected a model with three components (clusters). The optimal selected model according to BIC is "VEI" (e.g., variable, equal shape and orientation equal to coordinate axes) (Fig. 6a). The component variables are grouped into 3 clusters (e.g., 19 in cluster 1, 24 in cluster 2, and 7 in cluster 3). In cluster 1 there are 8 items from Gumelnița, 1 from Măgura-Jilava, 9 from Sultana and 1 from the Experimental batch. Cluster 2 contains 4 experimental items, 12 items from Gumelnița, 2 items from Măgura-Jilava, and 6 from Sultana. The rest of the clay weights, which were assigned to cluster 3 (7 items), are from Gumelnița (1), Măgura-jilava (4), and Sultana (2) (see Fig. 6b, c). The *fviz-mclust* function in the *factoextra R* package was used to visualize the clustering produced by the MBC [45]. Figure 6d provides the uncertainty cluster plot, where larger symbols indicate the more uncertain observations. As shown in the previously mentioned figures, most of the clay weights in our data set were assigned to cluster 2 (24) that include items from all the sites, and only a small fraction of them, were classified into cluster 3. Cluster 1 also contains items from all sites and the experimental batch, while the few clay weights assigned to cluster three are split between the three sites in the data set. It is therefore safe to say that while there are significant differences between sites, on a case by case analysis, for some technological as well as dimensional variables, there is not much inter-site variability overall, when technological variables are considered together; therefore the clay weights discussed in this paper are rather similar, irrespective of their provenance.

Discussion

The current multi-analytical approach of 64 archaeological samples (clay weights) from three different archaeological sites located in Romania coupled with the experimental study offer a new perspective on these items and a solid understanding of the *chaîne operatoire*. By visual and manual inspection, we conducted fabric analyses and techno-typological observations to obtain measures for dimensionality, weight of the samples etc. These investigations of prehistoric objects were augmented by the production of experimental replicas featuring certain site-specific characteristics, which were subsequently analyzed the in same manner as the archaeological specimens.

XCT-scan image analysis focused on analyzing the voids, cracks and inclusions apparent in the paste composition (Additional file 12: Table S10, Additional file 13: Table S11, Additional file 17: Table S14, Additional file 18: Table S15, Additional file 19: Table S16, Additional file 20: Table S17). We used as analytical criteria for those elements, their size, shape, position, frequency and distribution. Through image investigation, a series of details regarding the modeling techniques and the effort made by prehistoric potters to process (kneading and removal of impurities) raw material were identified (see also Additional file 14: Table S12, Additional file 10: Table S13, for detailed clay weights individual photography and XCT-scan image). The results from this multi-analytical approach allowed a series of distinct observations, regarding technological features of the investigated items.

Voids

All the scanned archaeological clay weights contain voids of different sizes from small (< 2.5 mm) to medium (2.5–7.5 mm) and large (> 7.5 mm), of ovoid or spherical, irregular and elongated or straight and elongated shapes, arranged vertically, oblique, and horizontally in

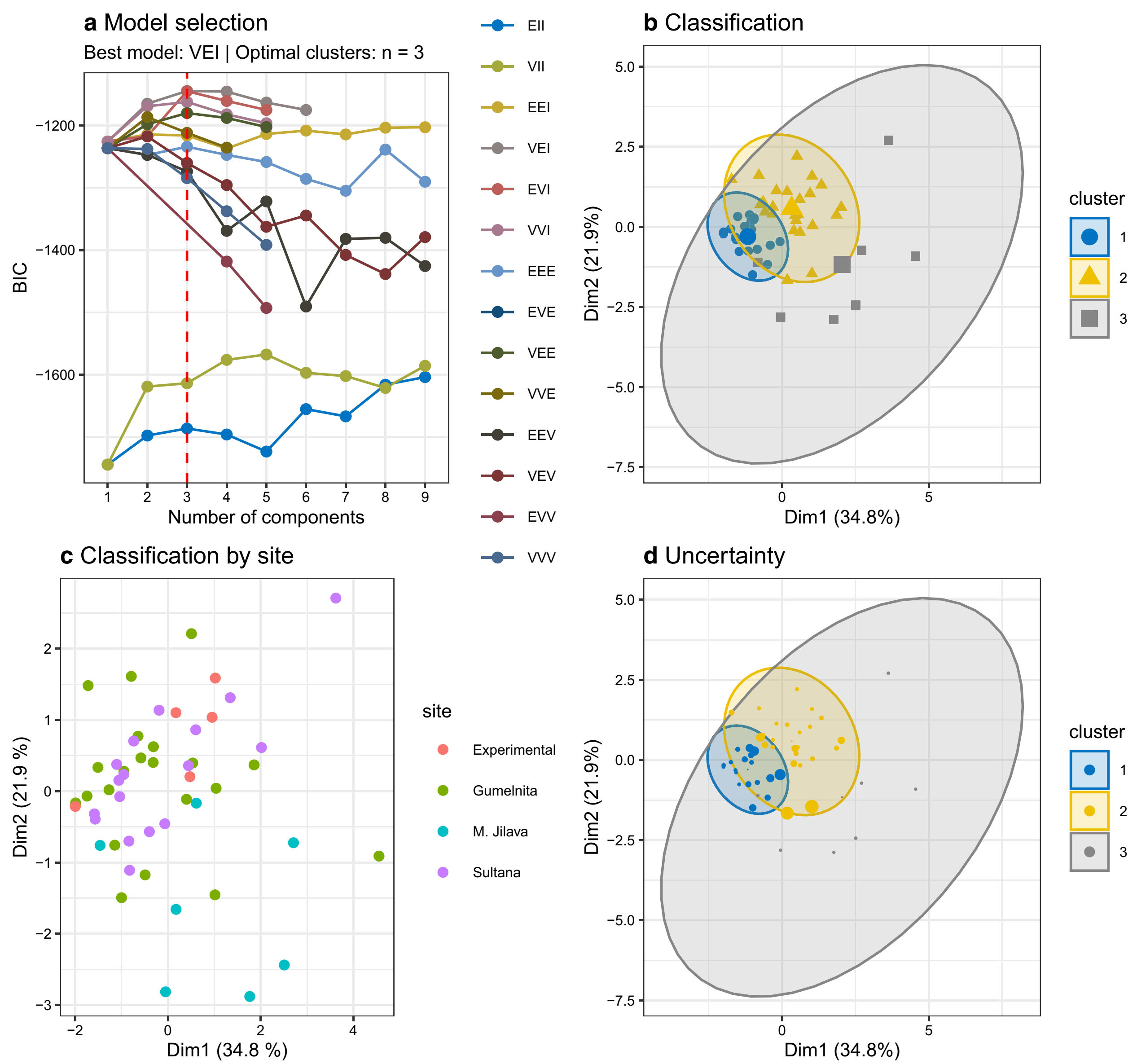

Fig. 6 Model-based cluster analysis of clay weights data set manufacture related categories: Inclusions frequency, Inclusions minimum size, Inclusions maximum size, Voids frequency, Voids minimum size, Voids maximum size. **a** Optimal number of clusters selection, using the Bayesian information criterion (BIC). Note the number of clusters suggested; **b** Model-based classification plot. Circles represent 95% confidence level ellipses; **c** Clay weights classification plot by site; **d** Model-based uncertainty cluster plot for the uncertain observations. Circles represent 95% confidence level ellipses. Note that the larger symbols indicate the more uncertain observations

the internal structure of the objects (Additional file 12: Table S10, Additional file 18: Table S15). While we know that each of these objects was modeled from a single clay piece, the orientation of the voids can help identify the detailed process of producing them. The specimens analyzed in this paper, irrespective of the site origin, show the same type of elongated voids, oriented mostly vertically, but also some horizontally, especially at the base of the pieces (Additional file 12: Table S10, Additional file 18: Table S15). These aspects indicate that, by using the fingers, the modeling technique was that of vertically pressing and stretching a clay piece until the desired shape was acquired. The fact that all the analyzed clay weights (except for a discoid one) are wider in the base, explains the appearance of horizontal or approximately horizontal voids in this area, as a result of lateral elongation.

Another aspect revealed by those voids, especially the larger ones, is the level of effort invested by the prehistoric people to prepare and model the raw material. Based on their morphology the larger voids have most likely occurred as a result of the kneading and/or modeling phases. More intensive kneading of the clay results in a more compact paste thus eliminating air voids. Given the fact that large voids are present in the internal structure of some clay weights from each location, but not in all of them, indicates that those voids occurred as a result of a process other than modeling or adding water, such as the disappearance of certain inclusions during firing.

The analyses show that many specimens originating from the site of Măgura-Jilava contain large voids (3 out of a total of 7), which may be due to a lesser effort spent in preparing the material. At the other two sites (Gumelnița and Sultana), the internal structure of the specimens reveals a lower frequency of voids than at Măgura-Jilava. Only 5 out of 23 specimens originating from Gumelnița have large voids, the same being the case for the clay weights from Sultana (5 pieces out of 27 scanned ones) (Additional file 12: Table S10, Additional file 18: Table S15). Based on these data we can suggest that the individuals who made the clay weights from the last two locations mentioned above were investing more effort into raw material preparation prior to modeling.

The rare frequency of voids (generally of small and in very few cases medium sizes) in the experimental clay weights (Additional file 13: Table S11, Additional file 20: Table S17) suggests that, unlike prehistoric potters, the members of the research team invested more effort into preparing the raw material prior to modeling.

Temper and Inclusions

The natural paste inclusions classified by their frequency (very rare < 1%; rare 1–3%; sparse 3–10%; moderate 10–20%; common 20–30%; very common 30–40%; abundant 40–50%), distribution, and sizes show an interesting pattern. Unlike those from Măgura-Jilava and Gumelnița, the ones from Sultana were made from clays with fewer impurities (Additional file 12: Table S10, Additional file 17: Table S14). This aspect may indicate a natural feature of the clay from this particular location, or the fact that individuals here have been more interested in the process of eliminating impurities.

In some cases (7 pieces from Sultana, 4 from Măgura-Jilava and 2 from Gumelnița) it was possible to identify the utilization of chaff as temper (Additional file 12: Table S10, Additional file 17: Table S14), based on the sparse and moderate frequency of the voids formed as a result of eliminating the vegetal matter during the firing process. Hence, we can say that the prehistoric people from Sultana and Măgura-Jilava chose to add this type of tempering agent when manufacturing clay weights.

In the case of four of the experimental clay weights, knowing that we added grog as temper, we can identify those particles by similarity in shapes and sizes, but we can also observe some larger different shaped grains (Additional file 13: Table S11, Additional file 19: Table S16). This aspect indicates that, despite carefully removing the impurities from the clay, few were still present in the final products (Additional file 10: Table S13).

Cracks

The occurrence of cracks inside several clay weights from all three archaeological sites (Additional file 12: Table S10) indicates that after modeling, the objects were left to dry either in a fluctuating temperature environment or for an inadequate amount of time.

The total lack of cracks in the experimental clay weights (Additional file 13: Table S11) indicates that drying the specimens in a constant temperature environment favored the bearing of physical stress during weight loss.

Fabric

The fairly consistent data set of clay weights that was available to us for this study (see sections above and Supplemental Materials), gave us the opportunity to ask a fundamental research question in respect with the technological production chains of Eneolithic clay weights. Our data set consisted of 64 clay weights recovered from three sites in Southern Romania (Gumelnița, Măgura-Jilava and Sultana). Only those (n = 61) keeping the whole range of sizes were considered for the dimensional analysis.

Techno-typologically investigation shows that ovoid shapes are more significantly preferred at Sultana and Măgura-Jilava, while at Gumelnița the clay weights are mostly pyramidal, although ovoid and other shapes do occur. The shape and the paste variables are not independent from each other, as shown by the highly significant results of Fisher's exact test (see also Fig. 4a). The dominant clay weights types (e.g., ovoid and pyramidal) being preferentially made from fine and semi-fine paste, and only a small fraction of the remaining shapes being made from coarse paste. The same highly significant connections at typo-technological level, holds true when surface treatment and clay weights types/shapes are concerned across sites. Here as well, Fisher's exact test is highly significant ($p = 0.002$, Fig. 4b). Gumelnița items are mostly smoothed and polished, a preference being given to polishing the pyramidal shapes as opposed to the ovoid ones, while at Sultana, most of the lay weights are ovoid and smoothed. Not much surface treatment is apparent on the rest of the clay weights types.

Paste and surface treatment of our artifacts are also highly significantly related, as shown by Fisher's exact test (p=0.02, Fig. 4c). Apparently, the prehistoric people at Sultana and Măgura-Jilava, preferentially smoothed the fine and semi-fine clay weights paste, while polishing is present at Gumelnița. The same is true for Măgura-Jilava sample. This sample is, however, rather small, and should be considered as such.

The results clearly showed that both archaeological and experimental artifacts share a similar mineral association, and common structural features, thereby supporting the idea that the clay used to make the prehistoric clay weights was collected from a local source, and the recipes used for their preparation were quite similar. Another important point to note is that grog, on average, represents 20% of the ceramic fragments paste composition.

Decoration

A differential pattern was also noticed for the decoration used on the clay weights. We noticed that across sites there is a significant relationship between the kind of clay weights paste and the number of items being decorated and the kind of decoration being used ($p<0.001$, Fig. 4d). As such, irrespective of paste type, the vast majority of clay weights at Sultana are not decorated, and none of the pieces from Măgura-Jilava are decorated. On the other hand, the opposite is true at Gumelnița, where almost all artifacts are decorated, the incision style being the most commonly used, and only one item made from undecorated coarse grained paste, undecorated. It is also important to note the fact that the majority of the Gumelnita weights were made from fine and semi-fine paste, too.

Size analysis

An interesting pattern has been revealed through the analysis of size clay weights variability across sites. Although the items from Sultana are the thickest of the entire sample, the results are not statistically significant neither at the level of the entire sample set, nor in a pair-wise comparison (Fig. 5a, Additional file 3: Table S8).

Clay weights are, on the other hand, significantly different across sites when it comes to height, and, in this case, the results are highly significant at both across all sites, as well as in two of the pair-wise analyses (Fig. 5b, Additional file 3: Table S8). Gumelnița clay weights are the tallest in the sample, followed by those from Sultana and Măgura-Jilava. Significant differences were observed between Gumelnița and Măgura-Jilava, as well as between Măgura-Jilava and Sultana, whereas the items from Gumelnița and Sultana could be considered similarly tall.

Clay weights in our sample are also considerably different with respect to their widths (Fig. 5c, Additional file 3: Table S8). The narrowest ones in the sample are those coming from Gumelnița, and widest being those from Sultana. Clay weights from all three sites are significantly different from one another in terms of width, showing a preference for broader items of this kind at Sultana, and slimmer ones at Gumelnița, and somewhere in between at Măgura-Jilava.

On the other hand, the analyses do not indicate any significant differences between sites with respect to the hole diameter. Although the hole diameter of the clay weights from Măgura-Jilava is the largest in the sample, the overall pattern is that the hole diameter is rather similar (Fig. 5d, Additional file 3: Table S8) for all sites.

Weight analysis across sites, on the other hand, did reveal significant differences among sites, overall, as well as, in a pair-wise comparison for two sites in the data set. The lighter items, from this perspective are registered at Măgura-Jilava (Fig. 5e, Additional file 3: Table S8), whereas the heaviest ones come from Sultana, seconded by those from Gumelnița. On pair-wise grounds, just as mean values show it (Additional file 3: Table S8), the significant differences are between Sultana (the heaviest ones) and Măgura-Jilava, as well as between Gumelnița (the second heaviest ones) and Măgura-Jilava (the lightest ones) (Fig. 5e). We can probably relate these differences to technological and, potentially, functional choices. One should also consider the kind and duration of firing process, as well as the potential secondary firing that some clay weights might had experienced, which might have contributed weight reduction.

While there is some variability between sites regarding the technological and dimensional variables, when each variable is concerned separately across sites, we also need to know whether this variability is high enough to produce distinct groups within or between sites that may be related to various technological choices of the prehistoric people that produced them. To understand this aspect of our study we employed a formalized method of cluster analysis called model-based clustering. As shown in the section dedicated to statistical analysis above, this method is less prone to effects of sample size and potential outliers in the sample, and it is useful for both univariate and multivariate data. The results provided by this method (Fig. 6a–d) group the technology related clay weights variables into three groups, based on the BIC (see above for details). The majority of them were assigned to clusters one (19) and two (24) and only 7 to cluster 3. All clusters thus contain variables from all three sites, with clusters one and two counting for the majority of the items.

Finally, what this implies, therefore, is that while some significant differences do occur, in a case by case analysis of both technological and dimensional variables, they are not, overall they are not the results of completely distinct technological and potentially functional choices on the part of those who made them. The MBC suggests that there might be rather more intra-site than inter-site variability in the process of clay weights manufacture recovered from the three sites discussed in this study.

Conclusions

The results provided by this multi-analytical approach provide new insights about the *chaîne operatoire* of the Eneolithic clay weights from Southern Romania. The benefit of this combinatorial approach of multiple methods can be seen throughout this paper. Thus, the multi-proxy investigation applied in this study, to both the archaeological and the experimental items, allowed the identification of various aspects involved in the clay weights manufacturing process, such as: the raw materials preparation, used recipes, fabrics component, techno-typological patterns, modeling and shaping, and human effort and time factor.

The current paper offers a new look at the production chain of the clay weights of the past people that lived 6000 years ago in one key region of the Balkans. Common technological traditions identified (e.g., shapes, sizes, paste composition, modeling methods, and surface treatment along with the decoration styles) allowed us to propose some general or particular production and consumption contexts of the human communities from the three sites investigated here. The differences in production chain processes highlighted by the experimental approach (replicas vs. archaeological items), suggest that the clay weights manufacture did not require a high knowledge of clay or advanced production technologies. However, on the other hand, our approach has also shown the existence of some production variables that are related to the collected raw materials, used recipes, and effort put by the craftsmen in this process. Additionally, some preferences in decoration of the items might have been linked to local styles of those past communities.

Using the XCT analysis of the archaeological items proved to be the right choice, in order to achieve the proposed objectives. It provided additional data to those offered by the technological-functional analysis, allowing an inspection of the internal structure of the investigated objects. Also, using experimental replicas as reference elements in understanding the manufacturing process of archaeological objects helped us in highlighting some invisible elements for the original items (e.g., the time required to manufacture or prepare the paste, effort per person, etc.), which otherwise could not have been estimated. In our opinion, the experimental approach presents a remarkable applicability that could be exploited in the future.

To conclude, the multi-analytical approach applied in this paper provides new results regarding the technological production of the clay weights from our target area, but it represents only a first step in this research direction. Without any doubt, the future use of other methods with higher accuracy will allow to identify other consistent and complementary information relative to these artefacts.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s40494-019-0326-2.

Additional file 1: Table S1. Clay weights data set.

Additional file 2: Table S2. Clay weights data set dimensions.

Additional file 3: Table S8. Clay weights data set sizes descriptive statistics distribution.

Additional file 4: Table S9. Sizes descriptive statistics distribution for the whole Clay weights data set.

Additional file 5: Table S3. Clay weights shape and paste distribution across sites.

Additional file 6: Table S4. Clay weights surface treatment and shape distribution across sites.

Additional file 7: Table S5. Clay weights shape and decoration type distribution across sites.

Additional file 8: Table S6. Clay weights paste and decoration distribution across sites.

Additional file 9: Table S7. Clay weights paste and temper distribution across sites.

Additional file 10: Table S13. Photos and images from XCT-scans for the experimental clay weights.

Additional file 11: Figure S1. Laboratory experimental firing chart.

Additional file 12: Table S10. XCT-scan analysis results for the clay weights archaeological sample.

Additional file 13: Table S11. XCT-scan analysis results for the clay weights experimental sample.

Additional file 14: Table S12. Photos and images from XCT-scans for the archaeological clay weights.

Additional file 15. Document S1. Rmarkdown document containing the R code for runing the statistical analyses.

Additional file 16. Document S2. Rproject file for replicating the statistical analyses performed in the paper.

Additional file 17: Table S14. XCT-scan analysis interpretation of inclusions for the clay weights archaeological sample.

Additional file 18: Table S15. XCT-scan analysis interpretation of voids for the clay weights archaeological sample.

Additional file 19: Table S16. XCT-scan analysis interpretation of inclusions for the clay weights experimental sample.

Additional file 20: Table S17. XCT-scan analysis interpretation of voids for the clay weights sample.

Abbreviations

XCT: X-ray computed tomography; MBC: model based clustering; BIC: Bayesian information criterion; ICL: integrated complete-data likelihood.

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Authors' contributions

CL supervised the study. BM, MD and TI performed the technological analysis of the archaeological artifacts. ML, FC, and RB performed the X-ray CT scans. GP performed the statistical analysis of data. BM, VO, and GP analyzed and/or helped to interpret the CT-scan data. BM made the experimental replicas, and quantification of the data. TI, MD, VP and VO provided samples and/or input about archaeological context. BM, GP, and CL wrote the manuscript with input from all co-authors. CL and GP have redesigned, corrected and improved the text based on recommendations made by the reviewers with input from BM, ML, FC, and RB. All authors read and approved the final manuscript.

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Availability of data and materials

The data sets supporting the conclusions of this article are included within the article and its additional files.

Competing interests

The authors of this article state that they have no conflicting interests.

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