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The rolling stones of Bronze Age Aegean: Applying machine learning to explore the use of lithic spheres from Akrotiri, Thera

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A R T I C L E I N F O

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A B S T R A C T

Across the Bronze Age Aegean and Eastern Mediterranean, various small spherical lithic artefacts have been discovered. The exact use of such artefacts remains a mystery, possible interpretations suggest that they are a form of counting system or counters for board games. This paper examines the largest collection of such artefacts found in the area to-date, the 746 spheres from the prehistoric town of Akrotiri in the island of Thera (Santorini). After the spheres were assessed and traditional statistical analyses were applied, machine learning was employed to further examine clustering of the spheres and to suggest potential interpretations of their manufacture, use and deposition. The paper concludes with the suggestion that the workflow proposed here, for Akrotiri, can be used to examine patterns in similar artefact groups from the Easter Mediterranean and beyond.

1. Introduction

The site of Akrotiri on the modern-day island of Thera (Santorini) (Fig. 1) is a well-known Bronze Age town that was destroyed by the eruption of the island's volcano during the Middle Bronze Age (possibly during the early 16th century BCE) (about Akrotiri see Doumas, 2017). In Akrotiri, among a wealth of finds, 746 spherical lithic objects have been catalogued, of which 65 % were brought to light in the recent excavations for the new shelter (Valacy, 2022) (Fig. 2). The spheres come in different sizes, colours, and stone materials, and have been found throughout the settlement, in both open and closed spaces. Small numbers of similar objects have been discovered in Cyprus and Crete (see Hillbom, 2008). Akrotiri, however, is unique due to the large number of spherical objects published to-date. The wealth of the spherical objects in Akrotiri, has resulted in different interpretations regarding their use by different researchers. Marinatos (1971: 28) interpreted the spheres as either sling stones or as tossing balls. Later, this interpretation was rejected by Valacy (2022) and Tzachili (2007). They suggest that the spheres are unlikely to have been sling stones as all other examples from this period, and from later periods, are generally heavier than most of the spheres from Akrotiri and are more ovoid in shape. Valacy and Tzachili suggest they are unlikely to have been used as tossing balls as they could easily harm the players if not caught. They agree, however, that the spheres may have been used as a counting/record-keeping system or as counters/pawns for a type of board game.

Previously, research on these spheres used multilevel modelling to investigate variability in sphere size within and between different areas of the settlement (sphere, excavation entity, and building complex) (Fernée and Trimmis, 2021). This research indicated there was greater variability occurring at the sphere level in comparison to excavation entity. This was interpreted as the spheres clustering in groups of different sizes within the different excavation entities and zones of the excavated town. This accorded with previously published research on the Akrotiri sphere assemblage. For example, a group of spheres excavated from the Western House come in a variety of sizes, from very small (16 mm in diameter) to large (45 mm). It was from this context that the hypotheses that the spheres were used as a counting system or game board 'pawns' were born (Tzachili, 2007). However, the analysis of Western House spheres was based on a very small assemblage, with a maximum of four spheres per excavation context, which is too small an assemblage to be statistically analysed.

2. Aims and objectives

Following the use of multilevel modelling and observations of greater variability in sphere size between spheres found together, the main aim of this paper is to explore the potential patterning within sphere concentrations. From this, the potential use of these spheres will be discussed. To achieve these aims, two objectives were put forward: 1) to statistically analyse the spheres based on their characteristics (size,

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weight, material, colour), and 2) Spheres that were discovered in the same archaeological context were further analysed for clustering using machine learning.

3. Materials and methods

3.1. Materials

A total of 746 lithic spheres have been excavated from a variety of locations within the site of Akrotiri. They comprise of a variety of lithic materials, colours and are both worked and unworked (Table 1; Table 2). A total of 621 spheres are worked, 121 are unworked and 4 spheres did not have any information on their surface form. Of the spheres excavated, 679 are complete and 67 are in-complete. Only complete spheres were included in the analyses presented in this paper. Of the complete spheres, 560 were worked and 119 were naturally formed. The complete spheres comprised of 14 different materials (Table 1). Sphere weight (g) and diameter (mm) was recorded for each sphere. The spheres were discovered in all parts of the settlement, quite often mixed within volcanic deposits. Of all the groups of spheres discovered, only four contexts, to date, comprise of more than ten spheres. Thus, following ‘traditional’ statistical analysis of the spheres, cluster analysis was undertaken on these four archaeological contexts (NFP643000EE, NFP26030_NE, NFP66P_1, NFP641_1). All contexts originate from Middle Cycladic, Middle Bronze Age, strata that were excavated during the rescue excavations for the new shelter pillars’ shafts in Akrotiri between 1999 and 2001. ‘NFP’ stands for new pillar shaft’ *(Νέο Φρέαρ Πεσσού in Greek),* then the first number indicates the number and location of the shaft. These excavations shed light on the phases of the Akrotiri town before the Late Cycladic phase when the town was destroyed by the volcanic eruption.

3.2. Methods

All data analysis was carried out in R (R Core Team, 2021). Data was first checked for normality (using a Shapiro-Wilk test) and for equal variance (using a Levene’s test). A One-Way-ANOVA test was used to compare differences between sphere material, colour and form (worked or natural) and sphere weight and diameter. If normality and equal variance were observed, a One-Way-ANOVA test was performed ($\alpha = 0.05$). When a statistically significant result was found, a Tukey HSD test was performed to identify which results were significant ($\alpha = 0.05$). Data that failed the normality and/or equal variance tests were analysed using the non-parametric Kruskal-Wallis on ranks test ($\alpha = 0.05$). When a statistically significant result was obtained, the Dunn’s method - a pairwise comparison procedure - was used to isolate the significant result(s). An association between sphere material and surface form (worked or natural) was tested using a chi-squared test ($\alpha = 0.05$). An intra-class correlation coefficient (ICC) (Shrout and Fleiss, 1979) was carried out to assess intra- and inter-observer reliability in obtaining

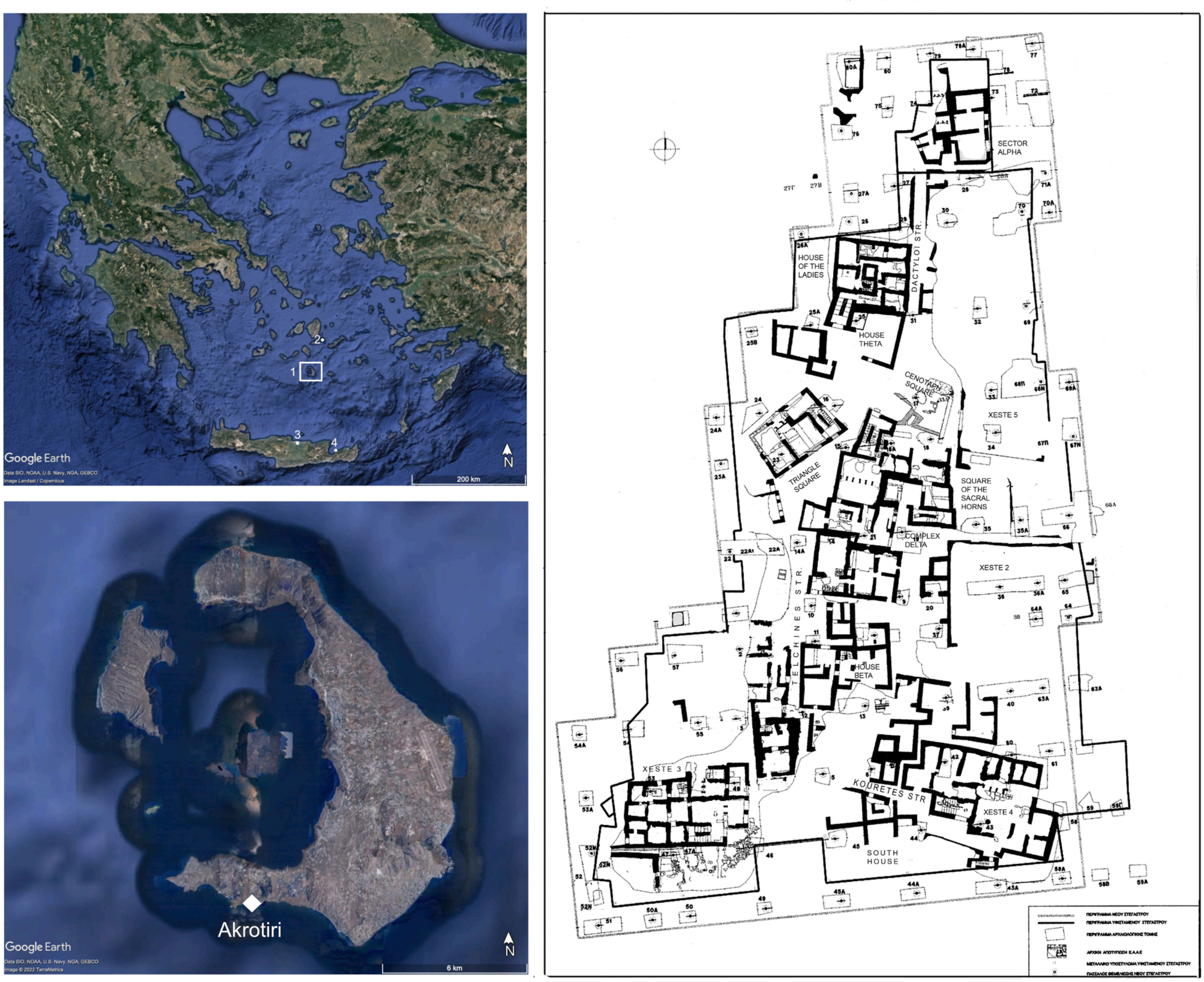

Fig. 1. A map of the main localities mentioned in the text, 1. is the island of Thera (Santorini), 2. the island of Keros, 3. Knossos, 4. Pseira. Along with the location of Akrotiri in Santorini and a plan of the excavated part of the settlement.

diameter and weight measurements.

3.2.1. Machine learning: Cluster analysis

Machine learning (ML) uses a range of different algorithms, depending on the questions being addressed, to explore and study data. There are 3 broad categories of ML: supervised learning, unsupervised learning and reinforcement learning. In supervised learning, a machine is taught by example; the algorithm is provided with a labelled dataset from which it models relationships between independent variables and a dependent variable. In unsupervised learning, the ML algorithm identifies patterns within unlabelled and unclassified data. Finally, reinforcement learning is learning from interaction; it trains algorithms using rewards and penalties to automate goal-directed learning and decision making (Sutton & Barto, 2018, see Jo, 2021 for an overview of the different ML methods). One of the main tasks of unsupervised ML techniques is clustering, also known as cluster analysis, which groups data into groups based on shared characteristics. This is an ideal tool to explore potential patterning in the sphere concentrations as, unlike other methods, it enables quantitative classification of groups without prior labelling.

Cluster analysis was performed to identify clustering in the sphere diameter and weight in R (R Core Team, 2021). Prior to analysis the measurements were standardised, due to the variables being on different scales. Before applying a clustering method, the data was assessed for the presence of clusters. A Hopkins statistic was used to assess the clustering tendency using the R factor extra package (Kassambara & Mundt, 2020). A threshold of 0.5 is often used to reject the alternative hypothesis and a value higher than 0.75 indicates a clustering tendency at the 90 % confidence level.

There are two main types of clustering algorithm: partitioning and hierarchical. Partitioning algorithms divide data in mutually exclusive partitions, this requires the provision of a number of clusters (k) before starting the algorithm. K-means and Partitioning Around Medoids (PAM) are both partitioning algorithms. K-means uses centroids, artificial points that represent the centre of the clusters, and PAM uses medoids, which are always the actual points in the dataset (Mondal and Choudhury, 2013). Hierarchical algorithms divide the data into a hierarchy of clusters, producing a dendrogram. Both types of algorithm were applied to the data to ensure the optimal clustering approach was adopted.

Table 1
Lithic material of spheres, with count, mean and standard deviation (sd) of weight and diameter.

Sphere Material	Count	Weight Mean (SD)	Diameter Mean (SD)
Agate	2	19.5 (0.71)	25.0 (0)
Andesite	29	36.28 (42.68)	28.31 (9.30)
Hornblade andesite	57	44.81 (38.09)	33.37 (8.37)
Limestone	52	41.17 (29.81)	31.56 (7.10)
Marble	10	49.2 (50.15)	32.0 (10.08)
Microdorite	4	33.50 (14.80)	31.00 (4.97)
Pebble	41	58.10 (42.98)	36.71 (7.04)
Pumice	12	81.92 (97.46)	48.00 (16.71)
Pyroxine andesite	4	67.25 (26.64)	39.25 (4.57)
Quartz	1	9	19
Sandstone	1	5	19
Tuff	430	29.25 (18.18)	33.10 (6.34)
Volcanic rock	27	54.07 (33.00)	35.41 (6.40)
UC	9	106.89 (97.84)	42.44 (11.65)

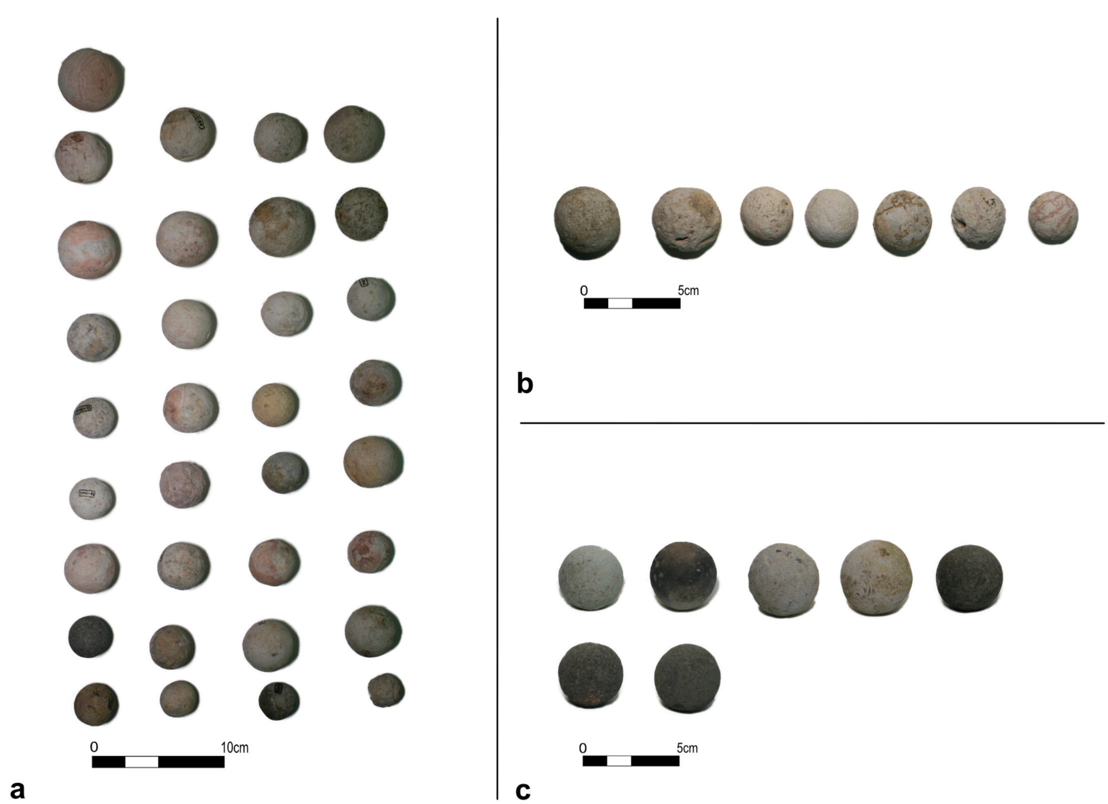

Fig. 2. a. Spheres group from context NFP643000EE b. Spheres group from room 5 Western House c. Spheres group from NFP64_1.

Table 2
Sphere colourcount, mean and standard deviation (sd) for weight (g) and diameter (mm).

Colour	Count	Weight Mean (sd)	Diameter Mean (sd)
Black	8	32.38 (34.91)	32.50 (7.29)
Brown	39	48.67 (58.55)	35.95 (9.93)
Grey	208	47.68 (42.96)	34.18 (9.03)
Pink	12	33.08 (18.54)	31.00 (6.32)
Red	21	44.38 (43.92)	33.67 (10.58)
White	382	29.77 (19.52)	32.89 (6.38)
Yellow	9	31.56 (11.96)	32.44 (5.39)

To identify the optimal clustering approach, an internal clustering validation procedure was carried out using the clValid package (Brock et al., 2008). This simultaneously compares multiple clustering algorithms to identify the optimal clustering approach and the optimal number of clusters. The three clustering algorithm mentioned above were compared: K-means, Hierarchical and PAM. These algorithms were compared using 3 internal validation statistics: connectivity, average silhouette width and Dunn index statistics. Connectivity indicates the degree of connectedness of the clusters, this has a value between 0 and infinity which should be minimised. The silhouette width and Dunn index combine measures of compactness and separation of the clusters. The silhouette width ranges from −1, poorly clustered, to 1, well clustered. In the Dunn's index the ratio between the smallest distance between observations not in the same cluster to the largest intra-cluster distance. It has a value between 0 and infinity and should be maximised. The number of clusters presented here were based upon the optimal number of clusters identified by these statistics.

4. Results

4.1. All spheres

4.1.1. 'Traditional' statistical assessment

A significant difference was found for material, colour and sphere form by weight and diameter in all instances apart from colour and diameter (Table 3). For sphere material and weight the significant differences were isolated as being between: Pebble and Andesite, Volcanic Rock and Andesite, Tuff and Pebble, Volcanic Rock and Tuff. For sphere material and diameter, the significant differences were isolated as being between: Pebble and Andesite, Pebble and Limestone, Pumice and Andesite, Pumice and Hornblade Andesite, Pumice and Limestone, Tuff and Andesite, Volcanic Rock and Andesite, and Tuff and Pumice. For sphere colour and weight, the significant difference was isolated between white and grey spheres, with grey spheres weighing significantly more than white spheres. Worked spheres were found to be significantly smaller (mean: 34.71 g and 32.97 mm) than unworked spheres (mean: 42.24 g and 35.67 mm). Finally, an association was found between sphere material and surface form ($p = <0.001$).

Table 3
Differences in weight and diameter by material colour and shape. †Failed Normality and/or Homogeneity Kruskal-Wallis rank sum test performed.

	Weight	Diameter
Material	<0.001*†	<0.001*†
Colour	<0.001*†	0.8437
Worked	<0.001*†	<0.001*†

4.1.2. Observer error

Intra- and inter-observer error was carried out on a sample of 110 spheres obtained from different contexts. The intra-observer error ICC value of 0.9787 was obtained, indicative of excellent reliability, with 95 % confidence intervals of 0.932 and 0.9838. The inter-observer error ICC value of 0.9996, again indicative of excellent reliability, with 95 % confidence intervals of 0.9994 and 0.9997.

4.2. Analysis by context

NFP643000EE: A total of 32 spheres were excavated in the context NFP643000EE (Fig. 3). This context is part of the excavations for the new shelter pillars, (New Pillar 64) at the eastern end of the excavated area and where Xeste 2 is located. The spheres were discovered grouped in a small artificial cavity at the eastern extension of the initial shaft as part of the Middle Cycladic horizon. All 32 spheres seem to have been placed deliberately in the excavated cavity that formed part of a, to date, unexplored building. All the spheres in this context were worked. The spheres comprised of 3 lithic types: Limestone, Tuff and Volcanic rock. However, the majority of the spheres were made of Tuff. The colour of the spheres varied, comprising of brown, grey and pink spheres (see Supplementary information).

When weight and diameter were tested for significant differences by material and colour, diameter was found to significantly differ by colour (Table 4). However, when the post-hoc test was performed it could not isolate the specific differences (Table 5). Brown and Grey spheres do, however, appear to have a smaller diameter than pink and white spheres.

When the clustering tendency of the spheres in Context NFP643000_EE was analysed the Hopkins statistic obtained ($H = 0.772$) indicated that clustering was present. The internal validation of the spheres in Context NFP643000_EE indicated that the optimal procedure is hierarchical clustering with 2 clusters present. In Table 6 this is indicated by the lowest connectivity statistic and the highest Dunn and Silhouette statistics. This suggests that spheres in this context are clustered in 2 groups. These groups comprise of a larger cluster of smaller spheres and a smaller cluster of larger spheres. A dendrogram can be used to explore the dissimilarity between the individual data points. The dendrogram in Fig. 3 shows the presence of two groups of spheres of

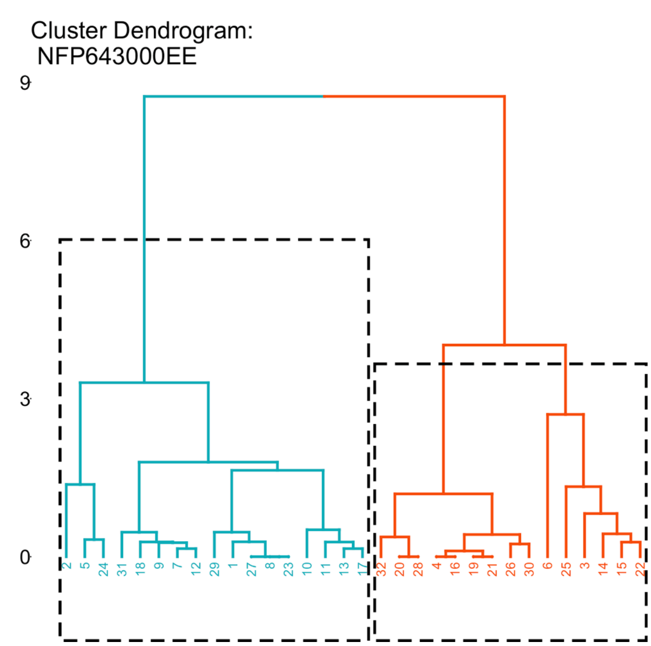

Fig. 3. Cluster dendrogram of the spheres excavated from NFP643000EE, the two clusters highlighted by the dashed boxes.

Table 4
Differences in weight and diameter of NFP643000EE spheres by material, colour and shape. [†]Failed Normality and/or Homogeneity, Kruskal-Wallis rank sum test performed.

	Weight	Diameter
Material	0.916	0.134
Colour	0.244[†]	**0.014** *
Worked	–	–

Table 5
NFP643000EE sphere post-hoc test results.

	Brown	Grey	Pink	White
Brown	–	–	–	–
Grey	0.7716	–	–	–
Pink	0.0613	0.1028	–	–
White	0.1028	0.1034	0.9717	–

Table 6
NFP643000_EE sphere clustering Internal validation statistic results (Connectivity: C, Dunn index: D and Silhouette: S). The optimal procedure is highlighted in bold.

		2	3	4	5	6
Hierarchical	C	**3.0540**	6.9552	12.5004	19.2361	21.0694
	D	**0.3105**	0.1287	0.1329	0.2354	0.2354
	S	**0.5445**	0.4961	0.4477	0.4576	0.4245
K-means	C	4.3198	11.3060	17.2698	19.6548	26.9730
	D	0.0750	0.1287	0.1343	0.1997	0.1997
	S	0.5297	0.4631	0.4493	0.4621	0.4091
PAM	C	4.3198	11.2750	19.7095	25.2548	27.9726
	D	0.0750	0.1172	0.0994	0.0994	0.1997
	S	0.5297	0.4018	0.3271	0.3875	0.4152

similar proportion (group 1: n = 17, group 2, n = 15).

NFP26030_NE: There were a total of 19 spheres in context NFP26030_NE. This context is from New pillar 26 which is located at the North East of the House of the Ladies, at the western extent of the excavated area. The finds are associated with a Middle Cycladic cobbled surface that may form part of an open space directly north of the House of the Ladies. All but one sphere was worked. The spheres comprised of 3 different types of material: Andesite, Hornblade Andesite and Tuff (See supplementary info). However, the majority were comprised of Tuff. The spheres were 3 colours: grey, pink and white. When weight and diameter were tested for significant differences by material, colour and worked, no significant differences were identified (Table 7).

When the clustering tendency of the spheres in Context NFP26030_NE was analysed the Hopkins statistic obtained (H = 0. 685) indicates some clustering in the spheres. The internal validation of the spheres in Context NFP26030_NE indicated that the optimal procedure was hierarchical clustering with either 2 or 6 clusters (Table 8; Figs. 4 & 5). The presence of 2 clusters is suggested by the low connectivity and high silhouette statistics (Table 8). Conversely, the presence of 6 clusters is indicated by the high Dunn statistic (Table 8). This suggests that spheres in this context are clustered in either 2 groups (of smaller and larger sphere sizes) or 6 groups of increasing sphere size. If the spheres

Table 7
Differences in weight and diameter NFP26030_NE spheres by material, colour and shape.

	Weight	Diameter
Material	0.979	0.374
Colour	0.95	0.639
Worked	0.363	0.742

Table 8
NFP26030_NE sphere clustering Internal validation results (Connectivity: C, Dunn index: D and Silhouette: S). The optimal procedure is highlighted in bold.

Algorithm		2	3	4	5	6
Hierarchical	C	**4.3758**	10.7690	18.0940	21.2774	24.0647
	D	0.3825	0.2194	0.3957	0.4177	**0.5874**
	S	**0.5448**	0.4628	0.5050	0.5068	0.3764
K-means	C	9.7099	13.6619	18.6063	21.7897	27.6742
	D	0.1700	0.2815	0.3717	0.4660	0.4104
	S	0.5003	0.4892	0.4982	0.5143	0.4382
PAM	C	9.3813	15.0909	17.7754	22.8091	27.6742
	D	0.0251	0.2245	0.4336	0.3688	0.4104
	S	0.3962	0.4826	0.5013	0.4654	0.4382

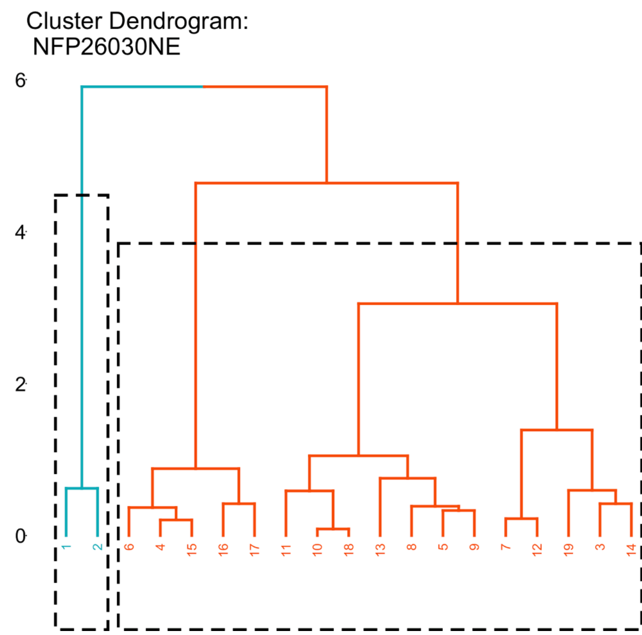

Fig. 4. Cluster dendrogram of the spheres excavated from NFP26030_NE, the two clusters highlighted by the dashed boxes.

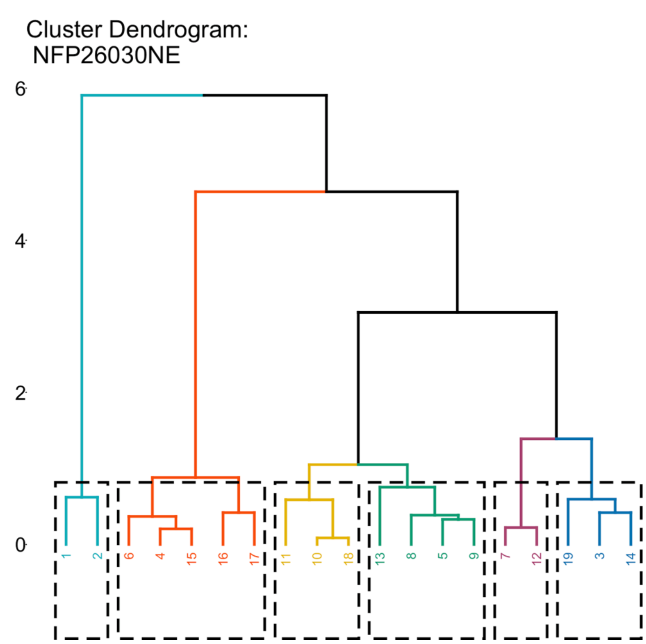

Fig. 5. Cluster dendrogram of the spheres excavated from NFP26030_NE, the six clusters highlighted by the dashed boxes.

are grouped into 2 groups, this would comprise of one larger more diverse group (n = 17) and 1 smaller homogeneous group (n = 2) (Fig. 3). Conversely, if the spheres are split into 6 groups these would comprise of similarly sized, both by group and sphere, groups (Fig. 4).

NFP66P_1: This context contained 28 spheres, of which 26 were complete and 2 incomplete. This context comes from New Pillar 66 at the eastern extent of the excavated area, between Xeste 2 and Xeste 5. This group of spheres were discovered in a small cavity of an interior space most possibly of Middle Cycladic date. Of the 26 complete spheres 19 were worked and 7 were naturally formed. The spheres were comprised of 6 different materials: Andesite, Hornblade Andesite, Limestone, Pebble, Tuff and Volcanic Rock. The spheres were 3 different main colours: grey, red and white (see Supplementary info). When weight and diameter were tested for significant differences by material and colour. No significant differences were identified. There was also no significant association (p = 0.056) between sphere form and colour (Table 9).

When the clustering tendency of the spheres in Context NFP66P_1 was analysed the Hopkins statistic obtained (H = 0. 814) indicates clustering was present. The internal validation of the spheres in Context NFP66P_1 indicated that the optimal procedure was hierarchical with 2 clusters (Table 10; Fig. 7). This indicates that spheres in this context are clustered in 2 groups. These groups comprise of a larger cluster of smaller spheres and smaller cluster of larger spheres. Fig. 6 shows the grouping of spheres into 2 groups, one larger and one smaller group.

NFP641_1: There were 17 spheres present in context NFP641_1. This context is part of the Middle Cycladic phase of NFP 64 and the group of spheres were discovered on the floor of a room. Of these spheres, 15 were worked and 2 were naturally formed. The spheres consisted of 4 different materials and 1 unclassified material. Finally, the spheres were either grey or white in colour (see Supplementary info). When weight and diameter were tested for significant differences by material and colour no significant differences were identified (Table 11). There was also no significant association (p = 0.072) between sphere form and colour.

When the clustering tendency of the spheres in Context NFP64_1 was analysed the Hopkins statistic obtained (H = 0. 771) indicate clustering was present. The internal validation of the spheres in Context NFP64_1 indicated that the optimal procedure is either hierarchical or k-means clustering with 2 clusters present (Table 12). This indicates that spheres in this context are clustered in 2 groups. Figs. 7 and 8 show the placement of spheres into the same groups by k-means and hierarchical algorithms. These groups comprising of a larger group of smaller spheres and a smaller group of larger spheres.

5. Discussion

By using a combination of 'traditional' statistical analysis and machine learning we can gain an insight into the possible reasons for sphere selection, sphere manufacture and sphere use. Across the whole site, worked spheres were found to be significantly smaller, in weight and diameter, than unworked spheres. This suggests that larger stones were collected whilst other stones were worked to make them smaller in size. Conversely, the significant difference in sphere size by material and colour is likely the result of the different properties of different types of

Table 9
Differences in weight and diameter of NFP66P_1 spheres by material, colour and shape. †Failed Normality and/or Homogeneity, Kruskal-Wallis rank sum test performed.

	Weight	Diameter
Material	0.5173†	0.382†
Colour	0.7904†	0.6757†
Worked	0.1931†	0.155

Table 10
NFP66P_1 sphere clustering internal validation results (Connectivity: C, Dunn index: D and Silhouette: S). The optimal procedure is highlighted in bold.

Algorithm		2	3	4	5	6
Hierarchical	C	**2.929**	8.3972	11.4512	15.3968	21.825
	D	**0.6181**	0.179	0.2436	0.2727	0.3163
	S	**0.7069**	0.54	0.4681	0.4252	0.4328
K-means	C	6.3325	9.3127	15.471	19.4167	24.8095
	D	0.1902	0.1297	0.1711	0.2147	0.1356
	S	0.6132	0.5208	0.4545	0.4557	0.4163
PAM	C	5.8044	15.1714	17.7643	21.7099	24.2849
	D	0.0967	0.0573	0.1444	0.1751	0.2794
	S	0.5509	0.3651	0.4272	0.4348	0.4203

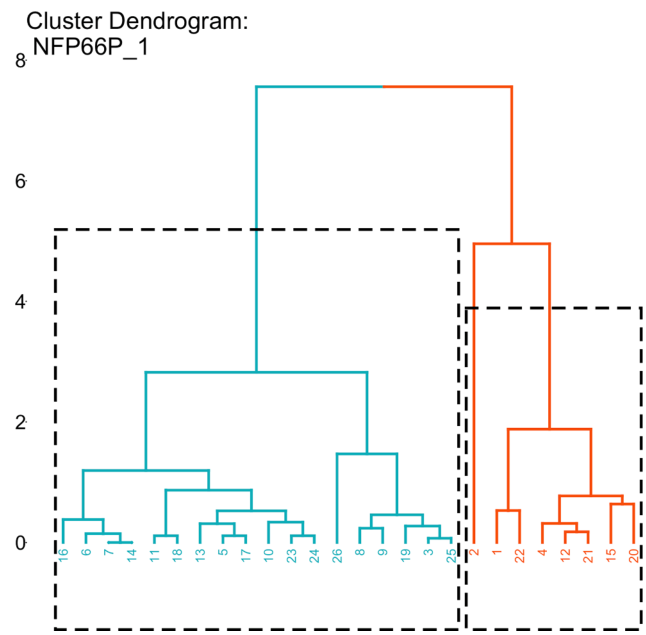

Fig. 6. Cluster dendrogram of the spheres excavated from NFP66P_1, the two clusters highlighted by the dashed boxes.

Table 11
Differences in weight and diameter of NFP641_1 spheres by material, colour and shape. †Failed Normality and/or Homogeneity, Kruskal-Wallis rank sum test performed.

	Weight	Diameter
Material	0.2142†	0.0678
Colour	0.1227†	0.851
Worked	0.5013†	0.45

Table 12
NFP641_1 sphere clustering internal validation results (Connectivity: C, Dunn index: D and Silhouette: S). The optimal procedure is highlighted in bold.

Algorithm		2	3	4	5	6
Hierarchical	C	**2.929**	7.327	11.7056	14.2056	22.6135
	D	**0.8631**	0.507	0.5724	0.5572	0.4528
	S	**0.674**	0.5989	0.5557	0.4899	0.4633
K-means	C	**2.929**	7.327	15.975	18.475	22.6135
	D	**0.8631**	0.507	0.25	0.25	0.4528
	S	**0.674**	0.5989	0.4687	0.41	0.4633
PAM	C	5.4937	7.327	11.7056	20.1135	22.6135
	D	0.307	0.507	0.5724	0.4098	0.4528
	S	0.6308	0.5989	0.5557	0.5078	0.4633

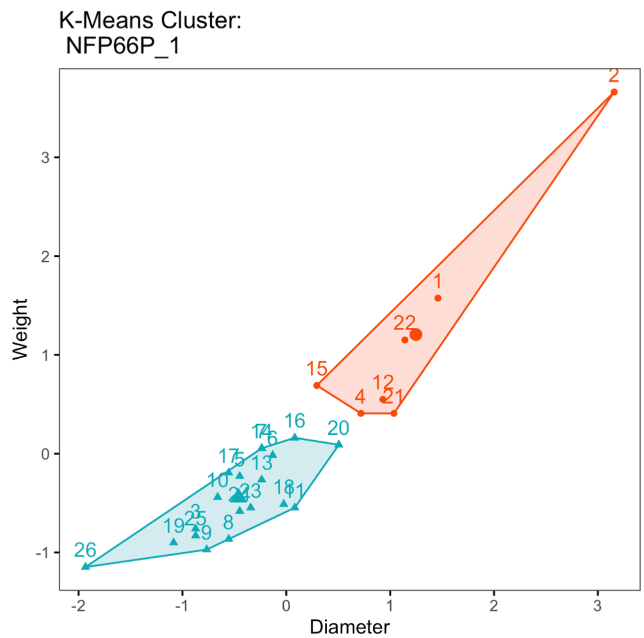

Fig. 7. K-means cluster of the spheres excavated from NFP66P_1 illustrating the two clusters (small and large sized clusters).

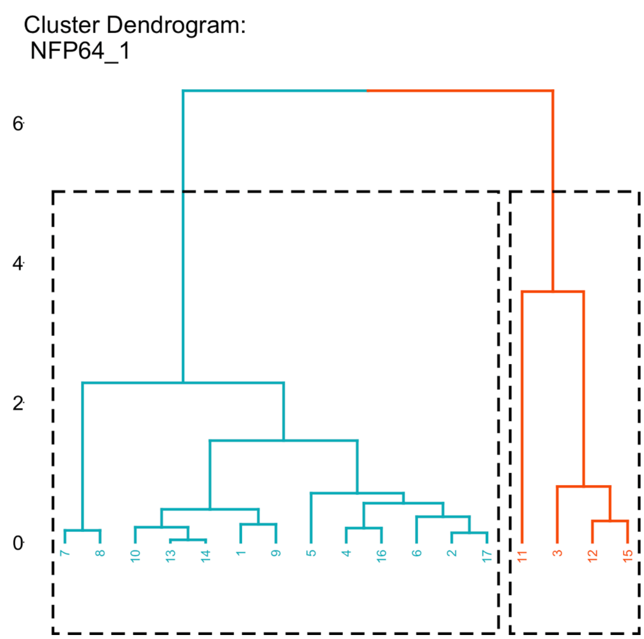

Fig. 8. Cluster dendrogram of the spheres excavated from NFP64_1, the two clusters highlighted by the dashed boxes.

stone; light and softer tuff in comparison with harder and heavier andesite and limestone. The application of machine learning indicates that patterning occurs in sphere size. In all contexts presented here, spheres cluster into two groups, one larger cluster that includes smaller spheres and one smaller cluster that includes the larger spheres. The analyses suggest that stones may have been deliberately selected or worked to fit the two general size clusters.

The clustering of the spheres into two groups do not support Tzachili's (2007) assumption that the stones form part of a counting or weighing system. In weighing or counting systems, the markers usually found in groups, have regular subdivisions of a larger unit, when the intervals between markers have some sort of regular occurrence, as is the case with the weights and counts that have been discovered in Akrotiri and across the Aegean (Michailidou, 2007: 207 – 230). If the spheres were part of a counting system, we would expect to see more clusters in more regular intervals. The clustering of stones, found in each context, into two larger groups, corresponds to Hillbom's (2008) idea that such spherical objects were counters/pawns for board games. Hillbom (2008) suggests that small spherical stone objects can actually be counters for games that were played on stone slabs with cup-marks/depressions, slabs that have been discovered all across the Eastern Mediterranean. These types of slabs have been found in Crete (Hillbom, 2008), the Levant (Sebbane, 2001), Cyprus (Crist, 2019), the island of Naxos (Renfrew, 1972), and indeed Santorini (Trimmis, 2021). What was shown from the recording of the slabs, also known as kernoi, in Akrotiri (Trimmis, 2021), and those found in Cyprus (Crist, 2019: 4–5), is that the function of the object was more important than its materiality. There are no patterns regarding the kind of stone that was used, neither the stones' colour nor general shape. It seems that a relatively flat slab that could be drilled or carved with cup-marks would do. The size of the cup-marks is not even equal between the slabs, and the only real pattern is the presence of one large mark along with several smaller ones – most possibly 21 in total – formed in a spiral or oval arrangement. For Hillbom (2008), if the slabs are indeed game boards, the counters could have been simple naturally occurring pebbles or even beans and pulses that were moved on the slabs by the players and not only lithic spheres. Focusing on Crete, Hillbom cites several spherical stone objects, that have been discovered in multiple locations across the island, made either from stone or clay, that can potentially fit the role of a counter (2008: 281 – 286). The dimensions of these objects (17 mm – 39 mm in diameter and between 29 g and 45 g in weight) correspond with the average of the stones' dimensions found in Santorini. All the spheres presented in Hillbom's study appear in very small groups of a maximum of two or three stones together. This makes distinguishing patterns problematic. Additionally, there has yet to be a stone slab discovered in context with an associated group of stones. Additionally, to Hillbom's review, spherical objects at various sites in Crete have been interpreted as sling stones. A well-known example are the spheres discovered at Pseira in the Plateia building (see Floyd et al., 1998). It is possible that these 'sling stones' were, in fact, counters for board games.

Similar spherical objects in very small contexts, of just few stones, with corresponding dimensions to those observed in Crete and Santorini, have also been discovered in other Aegean islands. Four spherical objects were found in Markiani in the island of Amorgos (Scarre, 2006: 180), while in Keros naturally occurring pebbles have been published by Renfrew et al. (2015). There is no clear reason why, so far, only in Akrotiri there has been such a large amount of spheres discovered in the settlement. One reason may be cultural; that only Akrotiri residents used lithic spheres, and in other locations counters were made from seeds, pulses, or dung-balls which have not survived post depositional processes. Otherwise, the absence of a large numbers of stone spheres elsewhere may be the result of research bias, with the stones remaining unnoticed during the excavation process (see also Hillbom, 2008: 277).

In Santorini, stone spheres have been discovered in contexts from all phases of the town, with most of the spheres coming from Middle Cycladic (Middle Bronze Age) strata. All four groups of spheres presented in this paper, along with one smaller group of four stones discovered at the Western House, have been placed together in artificial cavities below the architectural remains of the last Late Cycladic phase of the settlement. Notably, the four spheres from the Western House have been placed in the 'foundation pits' of the Western House, possibly as part of a ritual (Tzachili, 2007: 258). The deliberate deposition of MBA spheres as part of LBA activities in Akrotiri, in addition to fostering a perception of identity, memory, and continuity, is a strong indication of the importance that these spheres had for the society of the time. The social importance of the spheres, as indicated by the nature of this depositional practice, further supports the idea of the spheres being part of a game that was played for social interaction. Additionally, if the spheres are associated with the stone slabs, as Hillbom (2008) suggests, then they form part of a Middle Cycladic social activity that was not 'in fashion' during the last phase of the settlement. The stone spheres remained significant for the society of Akrotiri, as indicated by their treatment and ritual deposition, while the stone slabs fell out of use and were reused as building materials (Trimmis, 2021).

6. Conclusions

With the application of 'traditional' statistical analysis and machine learning on the Akrotiri spheres, this paper indicates that the spheres most possibly, have been collected or made to fit two major clusters, one of smaller and one of larger stones. The analytical methodology presented here can be further applied to groups of similar objects across the Aegean, including the large deposit of natural pebbles from Keros, to identify if similar patterns occur in other locations. The analysis of the spheres presented in this paper alongside the possible association between spheres and slabs (Trimmis, 2021), further support the hypothesis that the spheres were counters for a type of board game. However, to establish a clear link between spheres and kernoi further analyses need to be made of spheres and slabs with cupmarks, from both Crete and Santorini.

Data Availability Statement

The sphere data from this paper and the associated analytical code are available at: https://figshare.com/s/0c73d115c7d02472e301.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2022.103615.

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