A Novel Geometric Morphometric (GMM) Application to the Study of Bronze Age Tutuli

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ABSTRACT
In this paper we examine the morphological diversity of the tutuli object group from the Early Nordic Bronze Age onwards, an often over-looked artefact. With a significant presence throughout this period, and their widespread geographic and temporal distribution throughout the Nordic Bronze Age, tutuli are of great interpretive potential. Currently, only a few studies, focusing on the morphological diversity of tutuli have been published, consisting of accepted decades-old typologies. The objective of this paper is first and foremost methodological, examining two research questions grounded on the classification and periodisation of tutuli. Specifically, through an analytical and exploratory framework this article examines whether the breadth of archaeological tutuli shapes conform to the classificatory system of Montelius' typology, and whether a temporal relationship exists between specific tutuli types and shapes.

ARTICLE HISTORY
Received 18 February 2019;
Accepted 24 June 2019

KEYWORDS
Artefact analysis; Small finds; Quantitative analysis; Scandinavia; Ornaments

Introduction

From the beginning of the earlier Nordic Bronze Age (NBA henceforth), ranging from c. 1700-1100 BCE (following Nørgaard 2018), an expansion in the variety of material culture, owing to the introduction of the 'new' raw material, is witnessed. Through the medium of bronze, and its distinct new structural properties, an assortment of different object types were then made possible. With such an abundance of new material culture, many (often smaller) objects are frequently over-looked in archaeological studies. One such often-overlooked example to appear, which is the focus of this article, is the tutulus.

It is now accepted within archaeological literature on the NBA that tutuli are, to some degree, overlooked (Nørgaard 2018), and only superficially considered when present within large hoards (e.g. Aner 1962; Antiq. Tids. 1849-51; Frost 2008) or in extraordinary burials (e.g. Bergerbrant 1999; Boye 1896; Clausen 1990). An exception to this rule is Kristiansen (2013), who provides a general introduction into jewellery from Scandinavia. Kristiansen (2013:758) introduces tutuli by explaining, that "*the label tutuli (singular tutulus) was designated early on to distinguish some small circular plates, which have an eye or crossbar on the underside and a more or less protruding tip on the upper side*" (Figure 1). Another exception is Nørgaard (2018: 234-236), who thoroughly analysed and discussed the processes behind the crafting of tutuli, in addition to a broad collection of other Early NBA object types. In their form, tutuli vary considerably, from small and flat-plated morphologies to cone-shaped and even hemispherical shapes (Figure 2). And given their abundance throughout the NBA, spatially throughout Denmark, Sweden and Northern Germany, and chronologically throughout the entire Early NBA, as well as their sheer quantity, with over a thousand examples recorded in Denmark and Northern Germany alone (Aner et al. 1973, 1976, 1977, 1978, 1981, 1986, 1991, 1995, 2001, 2005, 2008, 2011, 2014; Aner and Kersten 1979; Aner, Kersten and Neuman, 1984; Aner, Kersten and Koch 1990; Aner et al. 1993), there is considerable interpretive potential in their analysis. (Figure 1 and 2)

Originally, tutuli were thought to have been designed for practical purposes with initial interpreta-

Figure 1. A cone-shaped tutulus (top left) and a flat-plated tutulus (top right). The lug on the underside of the cone-shaped tutulus is a crossbar (bottom left), while the flat-plated tutulus has an eye (bottom right). Not to scale. Photographs by Christina Vestergaard.

tions highlighting their function as shield-buckles (Rafn 1856). This viewpoint, however, stemmed from an incorrect interpretation of remains from an Early NBA burial at Buddinge, Sealand (Kristiansen 2013; Rafn 1856). Excavations at Buddinge revealed a Bronze Age individual, with wooden fragments positioned on the torso, which were in turn interpreted as the remains of a shield; it was hypothesised, that the tutuli bound the edges of the 'shield' together, thus providing a functional interpretation (Rafn 1856, 362). However, later investigations established that the wood belonged to a wooden coffin rather than a shield (Kristiansen 2013, 758). Excavations between 1878-1883 at Hesselagergaards Mark on the Danish island of Bornholm also questioned this notion, when four tutuli were recovered *in situ* and attached to remains of textiles. Sehested (1884, 51) argued that the tutuli could not be interpreted as parts of a shield as no wooden remains were recovered. Accordingly, a decorative and a more style-centric interpretation was provided (Sehested 1884, 51). Yet, several other function-based interpretations followed, including the use of tutuli as clothing buttons and/or as beltware (Bergerbrant 1999, 152; Broholm 1944, 107). In one particular example, Broholm (1944, 119) argues that when tutuli, and specifically flat-plated tutuli (Figure 2: Type A), were used by men, these functioned as cape buttons, while for women they fulfilled a solely aesthetic role. Nevertheless, with a lack of debate in the last few decades, and the absence of rigorous empirical frameworks, the functional and stylistic debate on tutuli remains open.

Here, we wish to focus on the strength of tutuli classificatory schemes, that is to say how tutuli are catalogued by archaeologists, and the degree of success in these morphological-based classifications. From the later part of the 19th century onwards, typological approaches were intgral to how archaeologists understood the Bronze Age and later prehistory in general. Hildebrandt (1866) was the first to apply a typological method on archaeological material, albeit with limited engagement with the archaeological material (c.f. Gräslund 1987). While establishing a typology, Almgreen (1967) notes that Hildebrand (1866) did not consider typological connections as a proxy for chronology. Building on from this, Montelius (1872) published his first typological frame-

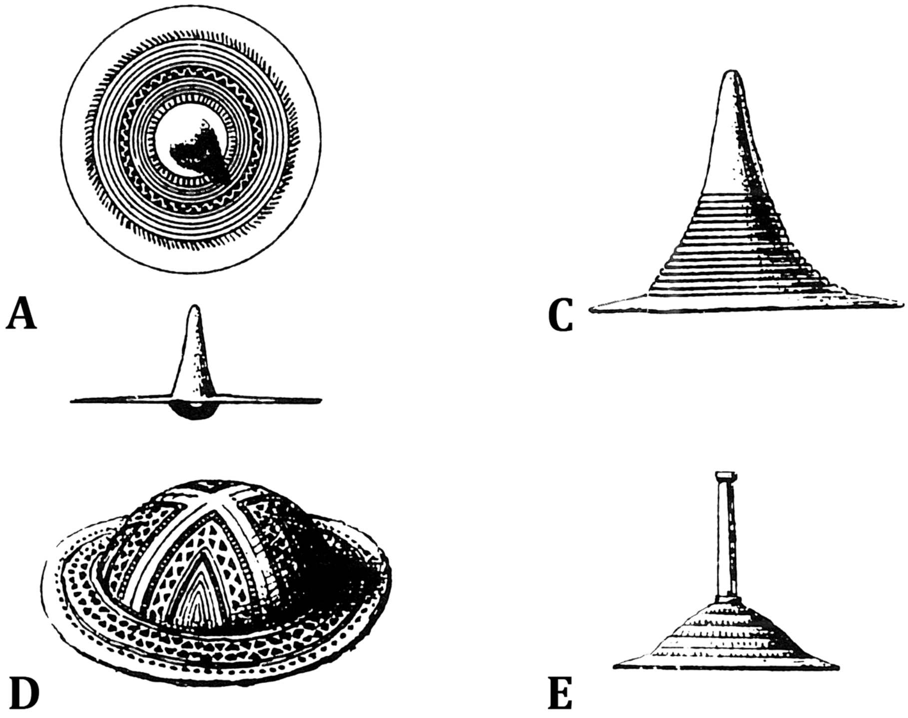

Figure 2. Montelius' four types of tutuli. Type A: a flat-plated tutulus (called belt discs by Nørgaard (2018, 234)); Type C: a cone-shaped tutulus; Type D: a hemispherical tutulus; Type E: a protruding tutulus with tip. Montelius' Types B and F (early and late belt plates respectively) are not accounted for in this article. The complete typology also accounts for belt buckles from NBA IV and NBA V (Montelius 1885, pl. 2 and 3).

work, encompassing a variety of material culture including fibulae, hanging vessels, shaft-hole axes, knifes and swords. Following this, Montelius (1875, 253) noted explicitly that the more important features of antiquities could be used to distinguish between different periods of the Bronze Age (Gräslund 1987), emphasising that Bronze Age burial customs, and changes in these customs, could underpin a chronological system within the Bronze Age. Resulting from these object typologies, Montelius (1885) established six periods (from NBA I to NBA VI). See Gräslund (1987) for further information on these subdivisions.

A number of other typologies have also been constructed, expanding from Montelius' mid-19th century classification (Baudou 1960; Kersten 1936; Laux 1971), grounded on artefact variability and their presence and/or absence; these are all of differing detail, and geographical and chronological focus. While Baudou (1960) only considered the Late NBA, Montelius (1885) paid particular attention to the Early NBA. Meanwhile, Laux (1971) and Kersten (1936) consider both the Early and Late NBA periods, but of differing geographic scope: Laux (1971) focused on the Lünenburger Heide (Lower Saxony) region of Germany, while Kersten (1936) focused broader. To further complicate the scenario, the starting points for the different typologies are quite different as Montelius (1885) considered the morphology of the tutuli, while Kersten (1936) constructed his groupings (and sub-groupings) through both the morphology and the decoration of the objects.

Given the lasting impact of Montelius (1885) on the periodisation of the Bronze Age (Bergerbrant 2007; Gräslund 1987; Hornstrup et al. 2012; Kneisel 2013; Kristiansen 2013; Vandkilde 1996; Vandkilde et al 1996), the framework's temporal scope, and the explicit focus on tutuli, this classificatory system is perhaps the best starting point, and most applicable method, for analysing the shape of larger tutulus datasets over multiple regions and periods. While so, the classificatory success is unknown; and it is unknown how idealised shapes account for the nature of variation as witnessed in the archaeological record. Furthermore, and building on from this, with an abundance of examples ranging throughout the NBA, it is unknown how tutuli shapes conform to the different periods of the NBA, if at all. This point of analysis is particularly delicate as the majority of contexts which contain tutuli have been dated relatively and lack an absolute date. We could be risking a circular argumentation when analysing the chronological distribution of types in a certain context, when such a context may have been dated only on typology. Hence, the chronological dating of the objects in question should not be considered as 'fixed' absolute chronologies – but rather as temporal periodisations.

Through this lens, the objective of this paper is first and foremost methodological, utilising a geometric morphometric (GMM henceforth) framework to answer two research questions (RQs):

1) *How robust is the Montelius (1885) classificatory system for cataloguing tutuli?*

2) *Do specific tutulus shapes conform to the temporal periodisation of the Early NBA?*

Examining RQ1 permits a greater understanding of – what can be understood as – one of the commonly adopted classifications for the Bronze Age, while RQ2 provides greater scrutiny on the tutuli as an artefact and where explicit changes in morphology can be seen throughout the Bronze Age.

Materials and Methods

To investigate these two RQs, catalogue drawings of complete tutuli cross-sections were digitised and analysed from a number of artefact catalogue publications (Aner et al. 1973, 1976, 1977, 1978, 1981, 1986, 1991, 1995, 2001, 2005, 2008, 2011, 2014; Aner and Kersten 1979; Aner, Kersten and Neumann 1984; Aner, Kersten and Koch 1990; Aner et al. 1993). Only illustrations of cross-sections were examined as this perspective is a standard perspective for illustrating tutuli and provides sufficient information to examine the Montelius (1885) classificatory scheme of periods. Furthermore, cross-section illustrations permit a complete analysis of artefact shape and all morphological information contained within the entire object. While illustrations can be viewed as both objective and subjective, demonstrating a "concourse between detail, realism, visuality and selectivity" (Lopes 2009, 14), similarly to lithic illustrations, their analytical potential should not be ignored. Of course, caution should be present when analysing illustrations as the main input of data, particularly as idealised characteristics may be overemphasised and subtle minutiae ignored. However, it is the authors' view that these actions may relate more to decorative elements on artefacts and not the artefact's morphology. Furthermore, with a standard suite of illustrative and technical signatures adopted throughout the catalogues, and a relatively large dataset, any such issues should be muted and insignificant when analysing artefact shape change.

The chronological information of the objects follows chronological determinations as recorded in the catalogue publications. As these catalogues do not use the Montelius (1885) typological framework on the recorded tutuli, and as no one corpus of tutuli feature such a classification, one author (CV) examined each tutulus cross-section and categorised as appropriate. While 1004 examples were recorded in the catalogues, the majority of the objects were fragmented or modified through post-depositional transformation and mechanical damage; a number of examples also lacked an illustration. Therefore, 376 tutuli are used to test the two RQs. It is important here to note that the examination of a classificatory scheme, and the first RQ, is through the success of the classification as per one individual and not on pre-existing designations. This is elaborated on further in the discussion section. For a breakdown of the temporal, geographical and morphological distribution of the tutuli sample see Table 1 and Figure 3.

As we wish to avoid absolute chronological assumptions in this paper, we consider the typology as a form of temporal periodisation, where types are combined in a relative order (see also Kneisel 2013). Montelius (1885) worked with six temporal periods (from NBA I to NBA VI) based on object typologies. Later subdivisions partitioned the Early NBA into six periods. However, this system has been argued to be difficult to practice (Hornstrup et al 2012; Zimmermann 1988), and hence this paper adopts the original division based on Montelius (1885). Only two of these defined periods consider the tutuli object group: NBA II, where Montelius (1885) place type A, C and D, and NBA III, where he placed type E. However, the reality is seldom clear-cut and hence overlaps are expected. Yet, as illustrated in table 1, Montelius' (1885) expectations

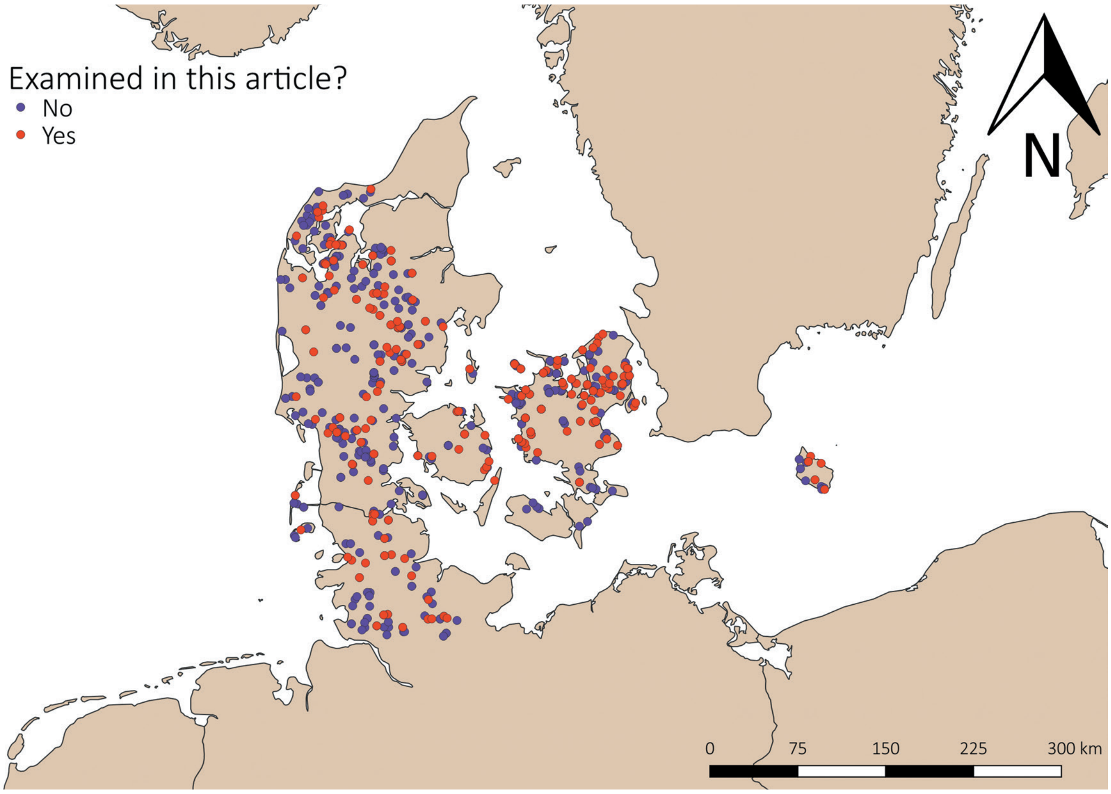

Figure 3. A map of all tutuli examined in this article (red) and all other recovered tutuli (purple).

		Type: Montelius (1885)				
		A	C	D	E	Total
Period	NBA II	136	84	51	5	276
	Transitional II/III	0	4	2	0	6
	NBA III	1	34	1	56	92
	LBA	0	1	1	0	2
	Total	137	123	55	61	376

Table 1. Rows: the dataset according to temporal periods of the NBA (as per the catalogue data); columns: the dataset according to types sensu Montelius (1885). Note: all objects have been accessed by CV and divided into the four typological groups by Montelius (1885). Sample size: 376.

are very close to the distribution of the objects in the dataset. However, it would not make sense to consider Montelius' (1885) expectations before we examine the robustness of his typology. Hence, this point will be revisited in the discussion part of this article.

Rather than attempting to record individual measurements and distances between diagnostic features (which are few in number) using traditional techniques (which are seldom straight-forward and feature a significant number of sources of measurement error), the cross-section was quantified and analysed through two-dimensional GMM. Over the last few years GMM methodologies have become routinely employed for the analysis of artefact morphology, providing a powerful statistical and exploratory framework for understanding artefact shape variance, the robustness of artefact groupings and temporal and spatial change in artefact shape (Birch and Martinón-Torres 2019; Bonhomme et al. 2017; Buchanan and Collard 2010; Freidline et al. 2012; Gilboa et al. 2004; Lycett et al. 2010; Wilczek et al. 2015). Shape is defined in this framework as the total amount of information which is invariant under

ID#	Description	Landmark category sensu Bookstein (1991)
1	Most proximal point of the tutulus tip (spike)	II
2	Midpoint of LM1 and LM3	III
3	Most distal point of the tutulus tip	II
4-5	Automatically produced equidistant landmarks (semilandmarks) between LM3 and LM6	III
6	Most-inner section of the curve between LM3 and LM9	II
7-8	Semilandmarks between LM6 and LM9	III
9	Most proximal point of the tutulus base	II
10	Midpoint of LM9 and LM11	III
11	Most distal point of the tutulus base	II
12-19	Semilandmarks between LM11 and LM20	III
20	Extremity of the tutulus cross-section	II
21-28	Semilandmarks between LM20 and LM1	III

Table 2. The landmark configuration (n=28) for the tutuli examined in this article. Note: the adopted semilandmarks represent a special 'Type 3' category through the Bookstein (1991) categorisation.

translation, rotation and isotropic rescalings (Small 1996). In this definition, and throughout this article, the analysis of shape does not include artefact size (which when combined define the form of the shape). This is noted in greater detail further in the discussion section of this article. Through GMM, landmarks (points of morphological correspondence) can be analysed, assessed through a multivariate framework and a continuous morphospace, thus allowing the reconstruction of mean and/or median shapes, in addition to cataloguing and displaying the total amount of shape diversity within a particular group of interest (Adams et al. 2004; MacLeod 1999; Navarro et al. 2004; Slice 2007; Zelditch et al. 2004). While researchers in the Bronze Age are becoming increasingly familiar with GMM approaches (e.g. Forel et al. 2009; Monna et al. 2013; Wilczek et al. 2015), there currently exists no examples of GMM analyses on tutuli, and accordingly a new workflow was necessary for this article.

The following procedure was therefore employed. Digitised images of tutuli cross-sections (scanned at 400 dpi), in TIFF format were first collated from the available catalogues (Aner et al. 1973, 1976, 1977, 1978, 1981, 1986, 1991, 1995, 2001, 2005, 2008, 2011, 2014; Aner and Kersten 1979; Aner, Kersten and Neumann 1984; Aner, Kersten and Koch 1990; Aner et al. 1993), converted into binary format, and synthesised into one thin-plate spline (.tps) file in the open-source tpsUtil v.1.69 software (Rohlf 2017a). A total of twenty-eight landmarks (2D cartesian coordinates) were then calculated for each image (i.e. each object) through tpsDig2 (Rohlf 2017b). These landmarks and semilandmarks (i.e. equidistant landmarks calculated through an algorithm) define the entirety of the object, correspond on all examples, and best represent points to anchor the range of morphological variability exemplified in the dataset. See Table 2 for definitions of each landmark and Figure 4 for a visual representation of the landmark configuration.

In order to extract the data by which shape variables are obtained from landmark data a Generalized Procrustes Analysis (Adams et al. 2004; Bookstein 1991; Gower 1975; Rohlf and Slice 1990) was performed. In this, all specimens were translated to a common origin (0,0), scaled to unit-centroid size, and through a least-squares criterion, were optimally rotated until all coordinates of corresponding point align as closely as possible. 78 iterations of this procedure were performed until maximum convergence was recorded (see R Script). Through this three-fold procedure, the resulting aligned Procrustes coordinates represent explicitly the shape of each specimen.

Using the Procrustes coordinates shape was first explored, through both period and the Montelius

(1885) classification system, by means of a Principal Components Analysis (PCA henceforth); see Jolliffe (1986) for an extensive review of PCA. The percent variation along each axis was noted through a scree plot, with relative positions in the morphospace represented for the range of variation within the dataset. The clustering for each period and classification is mapped through confidence ellipses (set to 75 %). Mean shapes for each period and classification type are also visualised. In exploring if specific tutuli shapes can be linked to different periods of the NBA, and if tutuli shapes can be successfully classified through Montelius' (1885) classificatory scheme, a discriminant analysis (Canonical Variates Analysis) of the first ten principal component scores (which represent 99 % cumulative shape variance), with leave-one-out cross-validation (jackknifing) was implemented. In following guidelines by Kovarovic et al. (2011) caution must be taken with certain groupings within the period-based analysis, as two groups ('Transitional Period II/III' and 'LBA') feature lower than the recommended group size (n = 40). While so, the classification correctness of NBA II and NBA III periods retain large dataset sizes and thus remain robust and are suitable to a discriminant analysis. No issues associated with dataset size are apparent with the Montelius classificatory-based analysis.

In complimenting this exploratory data exercise, the Procrustes coordinates were examined through a statistical framework, as to examine whether different periods of the NBA, and different types of the classification by Montelius (1885) are attributable to different shapes or trends to certain shapes. This was conducted through a Procrustes ANOVA (Goodall 1991), with the sum-of-squares calculated through 1000 permutations of the Procrustes process. Throughout this exercise an alpha level of 0.01 (significance level of 1 %) is adopted, with a null hypothesis (H0) of no difference between populations assumed.

All exploratory and analytical procedures were produced in the R Environment (R Development Core Team, 2014), using both the geomorph v.3.0.7 (Adams and Otárola-Castillo 2013) and Momocs v.1.2.9 (Bonhomme et al. 2014) packages. In promoting computational and research reproducibility, open science and data transparency (Marwick 2017) we attach with this article the .tps file, metadata (in .csv format) and R script (with extended commentary). A copy of all files can also be found on the Open Science Framework (OSF): https://osf.io/fcp43/.

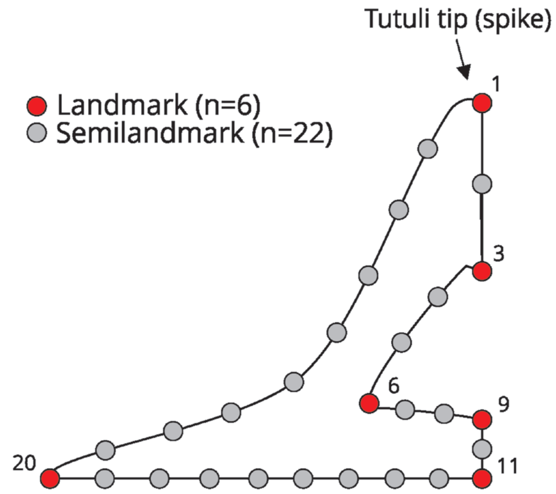

Figure 4. A visual representation of the landmark configuration used in this article.

Analysis

The first two principal components (main sources of shape variation for all tutuli) account for 84.3 % cumulative shape variance with the first five components accounting for 95 % cumulative shape variance, and the first ten components accounting for 99 % cumulative shape variance. This means, that 84,3 % of the shape variance of all objects analysed in this paper can be represented by two axes (or components), while the full morphological variance (or rather 99 % of the morphological variance) can be represented by ten axes. The first principal component extends from examples featuring a flat body and a slightly convex centre (more positive principal component one scores) to examples featuring a shorter and more pronounced cross-section (more negative principal component one scores). The second principal component extends from examples featuring a flat body and high central point (more positive principal component two scores) to a more domed and hemispherical tutuli appearance. When plotted through a two-dimensional tangent space (Figure 5a), clear subdivisions can be observed between the temporal NBA II and NBA III groups, with the NBA II/III transitional overlapping with both NBA II and NBA III. This is perhaps to be ex-

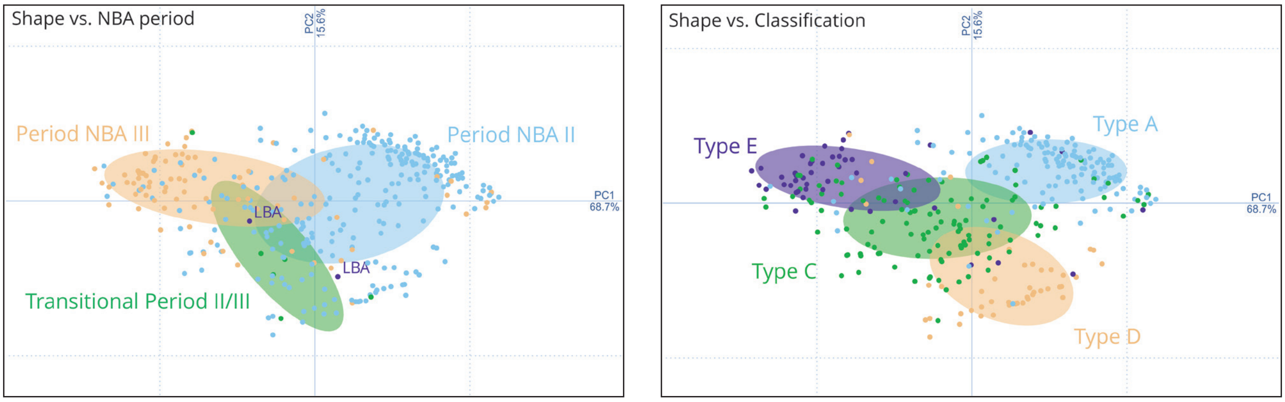

Figure 5. A principal component tangent space for the first two principal components (representing 84.3% cumulative shape variance), with morphospace positions for the axis ranges. Left: clustering according to NBA period for all tutuli examined. Right: clustering according to classification sensu Montelius (1885) for all tutuli examined. Confidence ellipses: 75%.

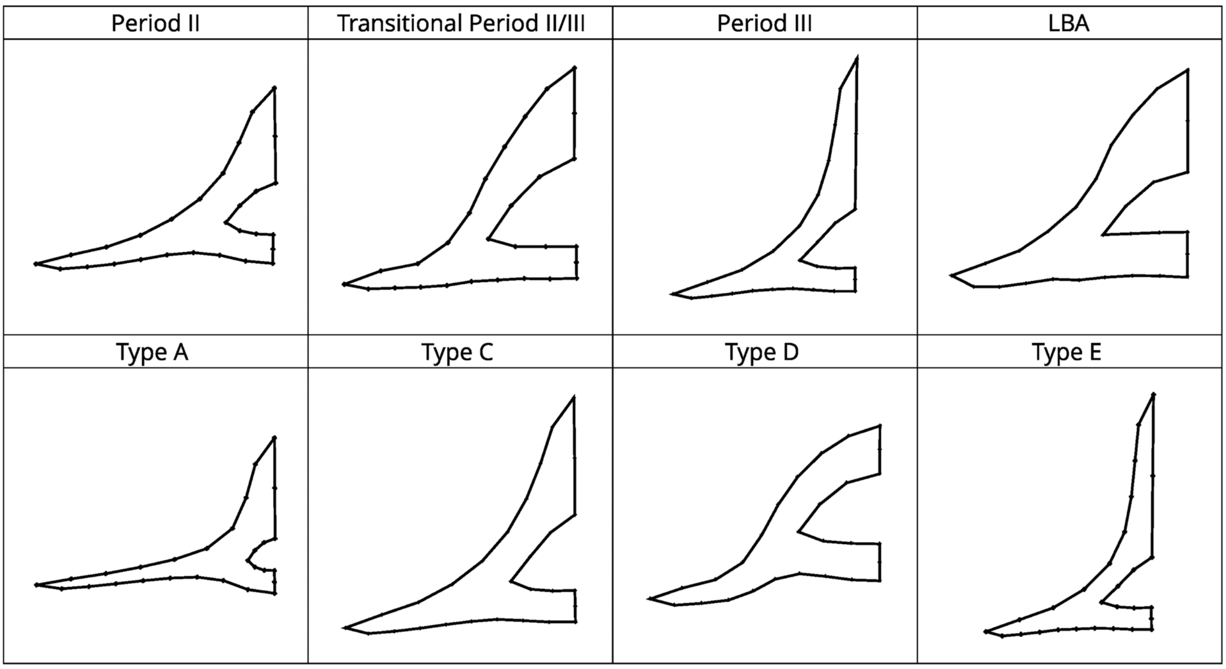

Figure 6. Mean shapes for both period (top) and Montelius' (1885) classificatory scheme (bottom).

pected considering that these tutuli originate from contexts with both NBA II and NBA III characteristics. NBA II examples feature more positive principal component one scores indicative of flatter tutuli cross-sections, while NBA III cluster towards more negative principal component one scores, indicative of more pronounced heightening in the centre of the tutulus. The two examples attributed to the Late Bronze Age feature no distinct spatial positioning. Interestingly, the four groups of Montelius' (1885) classificatory scheme do feature differing spatial clustering (Figure 5b) with minor overlap only documented between type C and all other types. In this, type A examples feature more positive principal component one scores, while type E forms feature more negative principal component one scores. The greatest differentiation between type C and type D forms lay in the second principal component, with type D examples featuring greater negative principal component two scores in comparison to all other groups. In their entirety, these two plots demonstrate the degree of success of the Montelius (1885) typology, and the observation of explicit shapes to different period. Mean shapes for each of the periods and groups can be seen in Figure 6.

The discriminant analysis further reiterates the trend and degree of dissimilarity as seen in the PCA (Figure 7). For the period-based classification of tu-

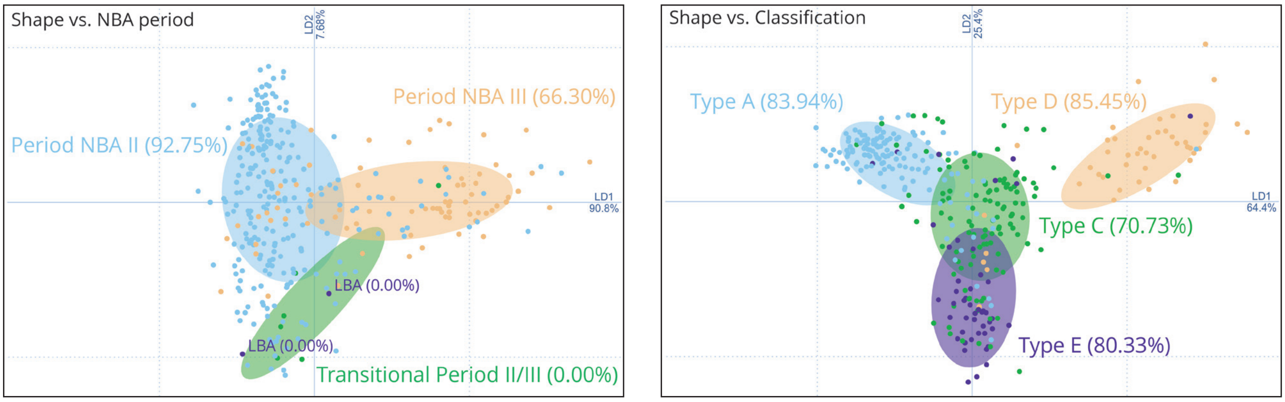

Figure 7. Discriminant analysis (Canonical Variates Analysis) for both classificatory schemes. Left: period-based classificatory scheme. Right: classificatory scheme sensu Montelius (1885). Percentages correspond to class correctness values.

tuli, differences between NBA II and NBA III can be observed, with the transitional group NBA II/III also appearing distinct (through confidence ellipses). Regarding the classificatory scheme, minor overlap is again observed for types A, C and E, with type D distinct from all three ellipses.

Through a jackknifing (leave-one-out cross-validation) procedure a high degree of classificatory success was noted with 84.3 % (317/376) examples assigned to the correct periodic group. In this a greater class correctness could be observed in the group NBA II with 92.75 % of examples correct classified, compared to 66.30 % success in NBA III. The NBA II/III transitional group and LBA examples could not be correctly classified, however, this is, as mentioned earlier, unsurprising given the low sample size. For the Montelius (1885) classificatory scheme, 79.3 % (298/376) of examples were correctly classified with over 80% class correctness for types A, D and E (83.94 %, 85.45 % and 80.33 % respectively) and a lower 70.73% class correctness for type C. Given its position within the PCA morphospace and the discriminant analysis (overlapping with type E and A) it is perhaps unsurprising that a lower-class correctness was calculated. The discriminant analyses in their entirety demonstrate that, to a high degree of correctness, random tutulus shapes can be assigned to the correct period-based and type-based classificatory schemes. For a more detailed breakdown of the discriminant analyses, please refer to the R script.

Finally, through a Procrustes ANOVA, this success in discriminating between tutuli is replicated for individual NBA temporal periods (*F*: 38.375, *Z*: 6.458, *p*: 0.001) and the Montelius (1885) typological scheme (*F*: 96.258. *Z*: 7.632, *p*: 0.001). Through these values both null hypotheses were rejected, and difference between types (groups/periods) concluded.

Discussion

Despite a lack of quantitative frameworks previously assessing the nature of these groupings, the GMM analytical and exploratory procedure demonstrated how robust both schemes are. In each of these schemes, a target shape is idealised with the true variability of shape fitting into these 'subjective' boxes. But however subjective these boxes may appear, they do stand up to scrutiny, and are useful classificatory schemes for the tutulus object group. Relatively high-class correctness scores were obtained, with differences in the exploratory visual exercise noted and statistical significance observed. And while not perfect, with roughly 20% of all examples incorrect in each classification, they are of merit to cataloguing NBA tutuli.

As mentioned in the methodology section, Montelius' (1885) typology was grounded through a temporal framework, in which type A, C and D 'belong' in the period NBA II, and type E in NBA III. As illustrated in Table 1, his expectations were met by the chronological information in the data source (i.e. the Aner and Kersten catalogues). As we established the robustness of Montelius' (1885) morphological types, we can hence discuss his expectations compared with the true variation observed in the archaeological record.

The majority of types A, C and D are placed in the group NBA II, with only a few objects placed in later – or rather in succeeding – periods. This is especially true for type A, where only one object is considered later than NBA II. Additionally, the majority of the type E objects are placed in NBA III. It does, however, seem that type C are more inclined to be distributed later than NBA II compared to types A and D. Even though only four objects are placed in the transition group NBA II/III (remember that only six objects are placed in this group) this type of tutuli may in fact be regarded as a transition type – maybe even a hybrid between type A (archetypical NBA II) and type E (archetypical NBA III). Type C does indeed share morphological characteristics with both of these types. It should however be mentioned, that type C contextually are often found with especially type A tutuli, but only seldom with type E (at least in the present dataset). Furthermore, the exploratory procedure (PCA variation and CVA scores) suggests greater variation in tutulus shape range in the early period, while later object groups exhibit tutuli of greater standardisation.

A temporal relationship between the types A, C and E is indeed suggested by Kersten (1936, 14-19, Abb. 1). However, his suggestion includes several other types such as the NBA III belt plate. It is not possible to determine a temporal relationship between these types based on the analyses presented in this article. We rather suggest that the temporal relationship between types A, C and E should not be understood as simplistic and evolutionistic as Kersten (1936, 14-19, Abb. 1) illustrates in his typology. More likely these types existed at the same time – although they may be inspired from one another – and gradually type C replaced type A, and later type E appearing more frequently than type C. This does indeed emphasise the temporal nature of the NBA periodisation.

In improving these classificatory schemes, we suggest four further avenues of research. First and foremost is the integration and pairing of examples with absolute radiocarbon dates to the above (or similar) GMM exercise. The majority of examples within this dataset are of poor chronostratigraphic setting and are based on contextual observations. For a more accurate scheme (through the assumption that specific shapes do always confirm to a specific period), and in building on from this article, the integration of robust chronological data is essential. This would furthermore change the perspective from a division-based periodisation to an actual fixed chronology. As we wish to maintain a methodological focus in this paper, this has not been pursued here. Furthermore, in examining morphological differences across Denmark, between the islands and mainland Jutland for example, an interesting avenue of research in testing these classificatory schemes further. It is generally understood that cultural differences, or according to Kersten (1936, 2) *cultural zones,* existed at this point in time; this does not only apply to the material record, but also to technical and crafting traditions (Nørgaard 2018), in addition to the pace of which new traditions were adopted (Randsborg 1968, 1972, 1987). This regional variation, which is particularly prominent in NBA III and IV (Hornstrup et al 2012, 10) is largely influenced by the number of objects originating from Zealand, totaling approximately 40 %, and one could hypothesise regional preferences in the style and use of tututli. While so, all four tutuli categories have been documented on Zealand, Funen and Jutland; further research could however test this observation further. Thirdly, for an improved classificatory scheme, further examples (with the available typological data) should be incorporated. Through the open-science approach adopted here, it is our hope that this dataset is re-analysed through other means and incorporated into other available datasets. To further test the robustness of Montelius' (1885) classificatory system, it is essential, that the experiment in recording through typology (as above) is replicated with multiple individuals, as a means of testing inter-observer error, in addition to the testing of examples where the classification has been applied. Finally, in improving these classificatory schemes a three-dimensional approach incorporating the whole artefact shape (and the factor of size) of tutuli is essential, incorporating surface data. With this available data, the analytical procedure can be more robust and more meaningful, taking into account a greater amount of data, and thus provide further insights into the meaning of NBA tutuli.

Conclusion

In its totality, this study demonstrates the strength of GMM methodologies for examining the variability in tutulus artefact shape, and its potential for better understanding the earlier NBA periods. With the methodology described above, utilising landmark and semilandmarks, tutulus cross-sections can now be catalogued to a high-resolution, and examined to better understand their underlying meaning, whether this be through the analysis and documentation of possible production centres or regionalised traditions (similarly to Wilczek et al. 2015), or through an assessment of artefact shape and their associated archaeological material. With these quantitative shape-based methodologies, there is now a potential to better understand the importance of tutuli throughout the NBA and provide an empirical framework for discussing their morphological change.

Acknowledgements

CSH is supported by grant #6107-00059B awarded by the Independent Research Fund Denmark. The objects in Figure 1 were made available for photography by Nordjyllands Historiske Museum (ÅHM-3726x3726A) and Vendsyssels Historiske Museum (VHM1635x01635) respectively. We thank Tibor-Tamás Daróczi and our two anonymous reviewers for their feedback and comments to this article.

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Supplement

id	artefact_id	site	date	classification	diameter_cm
1	1141III-1	Valbygård	II	C	4.8
2	1141III-2	Valbygård	II	A	6.6
3	1148-2	Landsgrav	II	C	4.8
4	1148-5	Landsgrav	II	D	4.65
5	1148-6	Landsgrav	II	C	2.55
6	1148-7	Landsgrav	II	C	3.9
7	1160-1	Svenstrup	II	D	4.65
8	1160-10	Svenstrup	II	A	4.5
9	1160-11	Svenstrup	II	A	4.65
10	1160-12	Svenstrup	II	A	4.65
11	1160-13	Svenstrup	II	A	4.05
12	1160-15	Svenstrup	II	A	4.05
13	1160-16	Svenstrup	II	A	4.35
14	1160-17	Svenstrup	II	A	4.05
15	1160-18	Svenstrup	II	C	3.45
16	1160-19	Svenstrup	II	C	2.4
17	1160-2	Svenstrup	II	D	4.5
18	1160-20	Svenstrup	II	C	4.05
19	1160-21	Svenstrup	II	C	3.15
20	1160-22	Svenstrup	II	C	2.85
21	1160-23	Svenstrup	II	C	3.45
22	1160-3	Svenstrup	II	A	4.65
23	1160-32	Svenstrup	II	A	4.65
24	1160-33	Svenstrup	II	A	4.65
25	1160-34	Svenstrup	II	C	2.4
26	1160-4	Svenstrup	II	A	5.7
27	1160-5	Svenstrup	II	A	4.2
28	1160-6	Svenstrup	II	A	4.65
29	1160-7	Svenstrup	II	A	4.35
30	1160-9	Svenstrup	II	A	4.65
31	1163A-1	Tårnborg	II	C	3
32	1163A-2	Tårnborg	II	C	3.3
33	1170	Ormslev	III	E	9.3
34	1274B-1	Ørslev	III	E	5.1
35	1274B-10	Ørslev	III	E	NA
36	1274B-11	Ørslev	III	E	NA
37	1274B-12	Ørslev	III	E	NA
38	1274B-2	Ørslev	III	E	5.1
39	1274B-3	Ørslev	III	E	5.1
40	1274B-4	Ørslev	III	E	NA
41	1274B-5	Ørslev	III	E	NA
42	1274B-6	Ørslev	III	E	NA
43	1274B-7	Ørslev	III	E	NA
44	1274B-8	Ørslev	III	E	NA
45	1274B-9	Ørslev	III	E	NA
46	1283-1	Store-Linde	II	C	4.05
47	1283-3	Store-Linde	II	D	4.65
48	131	Ferslev	II	A	4.35
49	1373-1	Sigerslevvester	II	D	6.15
50	1373-2	Sigerslevvester	II	D	NA
51	1384	Varpelev	III	C	3.75
52	1409-2	Sydsjælland	II/III	C	3.15

53	1420	Sjælland	II	A	NA
54	1422-1	Sjælland	II	A	4.05
55	1446-1	Krasmose	III	E	5.55
56	1446-2	Krasmose	III	E	5.55
57	1446-3	Krasmose	III	E	5.55
58	1446-4	Krasmose	III	E	5.55
59	1446-5	Krasmose	III	E	5.55
60	1464C	Stammeshalle	III	E	8.85
61	1482M	Jomfrugård	II	A	3.45
62	1492A-1	Limensgård	II	D	6.75
63	1492A-2	Limensgård	II	D	NA
64	14A-3	Bakkebjerg	II	C	4.2
65	150-1	Østby	II	A	7.35
66	150-4	Østby	II	C	4.2
67	152	Østby	II	C	5.1
68	1533	Lousgård	II	D	2.7
69	1760	Voldtofte	III	C	4.5
70	1777-1	Torøhuse	II	A	4.05
71	1777-2	Torøhuse	II	A	4.5
72	1777-3	Torøhuse	II	A	4.5
73	1777-4	Torøhuse	II	A	5.1
74	1777-5	Torøhuse	II	A	4.8
75	1777-6	Torøhuse	II	A	6.15
76	180-1	Lynge	III	D	5.55
77	180-2	Lynge	III	C	5.4
78	1820-1	Hasmark	II	D	4.2
79	1820-2	Hasmark	II	D	4.2
80	185A	Sigerslevvester	III	E	4.8
81	1868-1	Vellinge Mose	II	A	7.8
82	1868-2	Vellinge Mose	II	A	5.4
83	1868-3	Vellinge Mose	II	A	5.1
84	1868-4	Vellinge Mose	II	A	4.35
85	1868-5	Vellinge Mose	II	A	4.35
86	1868-6	Vellinge Mose	II	A	6.6
87	1868-7	Vellinge Mose	II	A	4.65
88	1944	Lumbygård	II	D	4.95
89	1960A	Rågelund	III	C	5.4
90	1960B-1	Rågelund	III	E	8.1
91	1960B-2	Rågelund	III	E	7.8
92	1960B-3	Rågelund	III	E	7.8
93	2011B-3	Hesselagergård	II	D	2.4
94	2019	Refsøre	III	C	4.05
95	2022	Davrehøjsmark	II	C	4.2
96	2039-1	Fæbæk	II	C	3.75
97	2138C	Bovense	II	C	3
98	2.16E+01	Smidstrupgård	II	D	2.4
99	2.16E+00	Smidstrupgård	II	D	NA
100	217	Smidstrupgård	II	C	2.85
101	218A	Vallerød	II	D	2.85
102	2234	Haurup	II	D	3.15
103	2266B	Massbüll	II	D	5.1
104	2292-2	Süderschmedeby	II	D	3.3
105	23	Smidstrup	II	C	3.15
106	2404-1	Schleswig	II	D	4.5
107	2409E	Schuby	III	C	3.9

108	2413-1	Schuby	II	D	3.9
109	2413-2	Schuby	II	D	NA
110	2414H	Schuby	III	E	5.7
111	243I-1	Præstegårdsmark	II	A	6.3
112	243I-2	Præstegårdsmark	II	C	3.75
113	243I-3	Præstegårdsmark	II	A	NA
114	2519D	Schoolbek	III	C	4.65
115	2553A	Sehestedt	II	C	2.1
116	2646B	Hedehusum	III	E	3.15
117	266	Farum	II	C	4.8
118	2669-1	Kampen	II	A	3.15
119	2669-2	Kampen	II	A	
120	278	Søsum	II	C	4.65
121	2816	Husum	III	C	1.8
122	281C	Søsum	LBA	D	3.9
123	2831	Ostenfeld	II	C	3
124	2844	Schobüll	II	D	2.85
125	294-1	Svenstrup	II/III	C	3.6
126	294-2	Svenstrup	II/III	C	3.6
127	2956-2	Fårhus	III	E	1.8
128	2962B-2	Frøslev	II	C	2.55
129	2979A-1	Padborg	II	A	4.95
130	297F	Store Salby	III	E	7.65
131	299-1	Ølby	II	D	3.45
132	299-2	Ølby	II	D	NA
133	299-3	Ølby	II	D	NA
134	3077A	Hønkys	II	C	4.8
135	3378-1	Sundbølgård	II	C	3.3
136	3378-2	Sundbølgård	II	C	2.85
137	3378-3	Sundbølgård	II	C	2.85
138	3378-4	Sundbølgård	II	C	2.85
139	3378-6	Sundbølgård	II	C	2.85
140	3378-7	Sundbølgård	II	C	2.85
141	3443-2	Hennekesdam	II	A	3.15
142	3443-3	Hennekesdam	II	A	4.65
143	347	Smørumnedre	II	D	2.85
144	353	Smørumovre	II	D	4.8
145	3600	Vojensgård	III	E	4.35
146	3601	Vojensgård	II	C	3.45
147	361	Bringe	II	C	3.6
148	3715-1	Toftlund	II	A	NA
149	3717A-2	Toftlund	III	E	2.1
150	378C	Bagsværd	III	E	9.3
151	379-3	Buddinge	II	C	3.15
152	379-4	Buddinge	II	A	4.65
153	379-5	Buddinge	II	A	6.9
154	379-6	Buddinge	II	C	5.1
155	379-7	Buddinge	II	C	5.1
156	379-8	Buddinge	II	C	NA
157	379-9	Buddinge	II	C	NA
158	3799A	Lejrskov	II	C	3.6
159	3817B	Hafdrup	II	A	3.75
160	3856	Tange	II	E	5.1
161	3866B	Gredsted	III	C	1.8
162	3919B-2	Tobøl	II	C	2.1

163	3919B-3	Tobøl	II	C	2.1
164	3919B-4	Tobøl	II	C	1.95
165	3939C-1	Nørre-Holsted	III	C	7.35
166	3939C-2	Nørre-Holsted	III	E	1.95
167	408-2	Rødovre	II	D	3.9
168	4084A	Lunde	III	E	1.95
169	411	Store-Magleby	II	D	2.55
170	417-1	Jægerborg Hegn	II	C	2.4
171	417-2	Jægerborg Hegn	II	C	3.15
172	417-3	Jægerborg Hegn	II	C	2.4
173	417-4	Jægerborg Hegn	II	C	3.15
174	4170	Søviggårde	II	C	8.4
175	426-1	Jægerborg Hegn	II	D	3.15
176	430	Søllerød	II	D	3.45
177	431	Søllerød	II	C	2.55
178	443-1	Petersdal	II	D	1.65
179	443-2	Petersdal	II	D	1.65
180	4513	Kobberdal	III	E	7.35
181	4544	Jelling	II	C	2.4
182	4574D	Bindeballe	II	D	3.75
183	460-2	Herslev	II	C	4.65
184	460-3	Herslev	II	C	4.35
185	460-4	Herslev	II	C	4.5
186	460-5	Herslev	II	C	4.35
187	460-6	Herslev	II	C	4.35
188	460-7	Herslev	II	C	4.35
189	460-8	Herslev	II	C	4.35
190	4602	Hanneup	III	E	4.8
191	4633	Ejsing	III	E	6.75
192	4654	Stendis	III	C	4.05
193	466C-2	Hvedstrup	II	D	4.35
194	4740A-1	Muldbjerg	II	A	3.45
195	4804	Kobberup	III	C	2.85
196	4858-2	Gudum	III	E	1.65
197	491	Roskilde	II	A	6.9
198	502-1	Lille-Valby	II	A	5.4
199	502-2	Lille-Valby	II	A	3.9
200	5085-1	Lækjær	II	D	3.3
201	5214A	Aldershvile	III	A	6.75
202	5227	Silstrup	II	E	4.95
203	5231B	Vorupørvej 16	III	E	1.65
204	525-1	Snoldelev	II	C	1.8
205	53-1	Lavø	II	A	5.1
206	53-2	Lavø	II	C	4.2
207	5353-1	Fredsø	II	D	3.15
208	5353-2	Fredsø	II	D	3.15
209	5379	Ljørslev	II/III	C	3.3
210	5530A	Aldrup	II	C	3.15
211	5557	Thy	LBA	C	2.85
212	556	Ledreborg	III	C	4.05
213	5616-1	Over-Torp	III	E	1.8
214	5616-2	Over-Torp	III	E	1.8
215	5638	Hald	II	C	2.55
216	5652	Toustrup	III	E	5.4
217	5663	Fur	III	C	4.8

218	5707A	Nautrup Hede	II	A	5.85
219	5735	Vile	III	C	5.7
220	5794	Ødeskovhede	II	D	5.25
221	590A	Ejby	II	E	7.05
222	5936A-C-1	Enslev	II/III	D	4.2
223	5936A-C-2	Enslev	II/III	D	4.05
224	5952D-4	Vranum	II	A	3.3
225	6003C	Torning	III	C	4.65
226	6008	Torning	II	D	2.7
227	6060	Middelhede	III	C	5.7
228	6099	Bækkelund	III	E	4.95
229	6121-2	Pederstrup	III	E	1.95
230	6132B	Tapdrup	III	C	5.7
231	6175-10	Møldrup	II	A	3.6
232	6175-3	Møldrup	II	A	3.15
233	6175-8	Møldrup	II	A	3.9
234	6175-9	Møldrup	II	A	3.45
235	6185	Højslev Mølle	III	E	2.1
236	6201A-1	Hverrehus	II	A	4.2
237	6201A-10	Hverrehus	II	A	4.2
238	6201A-11	Hverrehus	II	A	4.2
239	6201A-12	Hverrehus	II	A	4.2
240	6201A-13	Hverrehus	II	A	4.05
241	6201A-14	Hverrehus	II	A	4.2
242	6201A-3	Hverrehus	II	A	4.95
243	6201A-4	Hverrehus	II	A	4.2
244	6201A-5	Hverrehus	II	A	4.65
245	6201A-6	Hverrehus	II	A	5.1
246	6201A-7	Hverrehus	II	A	4.95
247	6201A-9	Hverrehus	II	A	3.9
248	6201E	Hverrehus	II	A	3.9
249	6254A	Briksbjerg	III	C	4.2
250	6268-2	Lihme	II	C	3
251	6347B	Nørgård	II	A	NA
252	6403-1	Nørbæk	III	C	2.1
253	6403-2	Nørbæk	III	E	4.8
254	6404	Nørbæk	III	E	5.7
255	6452	Hårup	III	C	3.45
256	6455	Hårup	III	C	1.8
257	6460B	Linå	III	C	4.2
258	6461	Linå	III	E	7.05
259	6482-1	Silkeborg	II	C	3.15
260	6482-2	Silkeborg	II	C	3.3
261	649B	Asnæs	III	E	4.95
262	6585-3	Legårdslyst	II	D	1.95
263	6585-4	Legårdslyst	II	C	3.6
264	6648B	Hvidsminde	II	A	3.3
265	6653C-1	Nim	III	E	3.3
266	6653C-2	Nim	III	E	2.85
267	669-1	Rye	II	A	6.3
268	669-10	Rye	II	A	5.4
269	669-11	Rye	II	A	3.45
270	669-12	Rye	II	A	5.4
271	669-13	Rye	II	A	5.4
272	669-14	Rye	II	A	5.7

273	669-15	Rye	II	A	6.15
274	669-16	Rye	II	A	6.3
275	669-18	Rye	II	A	5.1
276	669-19	Rye	II	A	6.75
277	669-2	Rye	II	A	4.8
278	669-20	Rye	II	A	5.1
279	669-21	Rye	II	A	5.1
280	669-22	Rye	II	A	6.75
281	669-23	Rye	II	A	6.9
282	669-3	Rye	II	A	4.05
283	669-4	Rye	II	A	6.6
284	669-5	Rye	II	A	7.35
285	669-6	Rye	II	A	7.35
286	669-8	Rye	II	A	5.1
287	669-9	Rye	II	A	5.1
288	6700A	Lykkensspil	III	C	5.7
289	6711	Grædstrup	II	A	5.1
290	6750B	Troelstrup	III	C	5.1
291	6827	Naldal	III	C	3.45
292	6884C-2	Hundshoved	III	E	1.8
293	6928C-1	Højballegård	II	C	5.55
294	6949	Knudrisbakke	II	C	4.2
295	708-1	Kongsted	II	A	8.4
296	708-10	Kongsted	II	A	5.55
297	708-11	Kongsted	II	A	5.25
298	708-12	Kongsted	II	A	4.2
299	708-13	Kongsted	II	A	4.05
300	708-14	Kongsted	II	A	6.6
301	708-16	Kongsted	II	A	6.3
302	708-17	Kongsted	II	A	5.1
303	708-18	Kongsted	II	A	4.8
304	708-19	Kongsted	II	A	4.35
305	708-2	Kongsted	II	A	10.05
306	708-20	Kongsted	II	A	4.95
307	708-3	Kongsted	II	A	8.1
308	708-4	Kongsted	II	A	6.3
309	708-5	Kongsted	II	A	4.65
310	708-6	Kongsted	II	A	6.9
311	708-7	Kongsted	II	C	3.6
312	708-8	Kongsted	II	A	7.05
313	708-9	Kongsted	II	A	5.55
314	74-2	Ågerup	III	C	6.6
315	744	Ods	II	C	3.9
316	745	Ods	II	C	4.2
317	746	Ods	II	A	4.05
318	761B-5	Høve	II	A	4.95
319	761B-6	Høve	II	A	6.9
320	761B-7	Høve	II	A	5.25
321	761B-9	Høve	II	A	4.35
322	825-1	Annebjerg Skov	II	D	5.55
323	872	Nykøbing Sjælland	III	C	4.05
324	896B	Hønsinge	II	A	4.05
325	9363A-1	Drage	II	D	5.85
326	9363A-2	Drage	II	D	5.85

327	945D-1	Sælvig	II	C	3.6
328	9462A-2	Wrack	II	E	2.1
329	9481B-1	Puls	II	D	4.35
330	9481B-2	Puls	II	D	3.45
331	9504-1	Vaale	II	A	6.3
332	9504-2	Vaale	II	A	6.9
333	9515B-1	Warringholz	III	E	1.95
334	9515B-2	Warringholz	III	E	1.8
335	9700	Schmalstede	II	E	1.8
336	973-1	Eskebjerggård	II	A	4.95
337	973-2	Eskebjerggård	II	C	4.65
338	976-1	Eskebjerggård	II	A	4.65
339	976-12	Eskebjerggård	II	A	3.45
340	976-13	Eskebjerggård	II	A	3.15
341	976-14	Eskebjerggård	II	A	3.3
342	976-3	Eskebjerggård	II	A	4.05
343	976-4	Eskebjerggård	II	C	3.9
344	976-7	Eskebjerggård	II	A	3.9
345	976-8	Eskebjerggård	II	A	4.05
346	976-9	Eskebjerggård	II	A	3.6
347	9765	Gadeland	III	E	2.55
348	9816B-2	Bornhöved	III	C	5.25
349	9816B-3	Bornhöved	III	C	2.7
350	9841	Bornhöved	III	C	3.75
351	998-1	Kilshoved	II	A	3.3
352	998-2	Kilshoved	II	A	3.45
353	999-1	Mastrup	II	D	2.85
354	999-2	Mastrup	II	D	NA
355	9992C	Tarbek	II	C	2.7
356	1199	Sønder-Bjerg	II	C	2.55
357	3369	Tornum	III	C	4.05
358	5501A	Villerup	III	C	3.45
359	6121-1	Pederstrup	III	E	2.55
360	708-18	Kongsted	II	A	4.8
361	9911	Gross Kummerfeld	III	C	3.3
362	1000-2	Mastrup	II	C	3.45
363	1013B-1	Birkendegård	II	C	3.6
364	1013B-2	Birkendegård	II	C	3.15
365	1013B-3	Birkendegård	II	A	3.6
366	1013B-4	Birkendegård	II	A	3.6
367	1013B-5	Birkendegård	II	A	3.6
368	1013B-7	Birkendegård	II	C	2.85
369	1051B-1	Næsby	III	E	4.05
370	1051B-2	Næsby	III	E	5.25
371	1070-2	Bognæs	II	D	4.05
372	1077-1	Løserup	II	A	4.35
373	1077-2	Løserup	II	C	3.75
374	1077-3	Løserup	II	C	2.55
375	1111B-3	Ringstedmark	II	A	1.8
376	1121	Boeslunde	II	D	3.9