



Geometric morphometrics sheds new light on the identification and domestication status of ‘new glume wheat’ at Neolithic Çatalhöyük

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ABSTRACT

‘New glume wheat’ (NGW) is an archaeobotanical type increasingly recognised at Neolithic–Bronze Age sites across Europe and Western Asia. NGW has been recognised via aDNA and morphological analyses of chaff remains as a member of the *Triticum timopheevii* wheat group, recent cultivation of which is known only from western Georgia. This study combines geometric morphometric (GMM) analysis of NGW grains with updated results from a parallel study of chaff dehiscence, to assess the taxonomic classification and domestication status of NGW from the Neolithic East Mound at Çatalhöyük (central Anatolia).

Results confirm close comparability of NGW with modern wheats from the group *T. timopheevii*, in a form which has remained remarkably similar over thousands of years. Furthermore, the analysis suggests that NGW was undergoing selection for domestication traits in terms of shattering behaviour and grain form during the 1150-year East Mound sequence. These findings are interpreted in the context of substantial archaeobotanical evidence for a broad-spectrum plant strategy at Çatalhöyük which mitigated the risk of resource failure and supported experimentation in cropping. Possible cultural and practical incentives are considered for investment in the crop, made despite the availability of a fully-domesticated glume wheat (emmer) with similar growing and processing requirements. Alongside this, the study demonstrates the sensitivity of GMM to differences between and within wheat species, with methodological findings that can inform future studies.

1. Introduction

1.1. ‘New glume wheat’

‘New glume wheat’ (NGW) was characterised by Jones et al. (2000) from a distinct group of archaeobotanical spikelet bases recovered from Neolithic and Bronze Age sites in northern Greece. Based on the chaff morphology and grain:chaff ratios of deposits it was concluded that these were remains of a tetraploid wheat. Of the modern specimens compared, Timopheev’s wheat (*Triticum timopheevii* Zhuk.) most closely resembled the morphology of this newly-identified archaeobotanical group.

The *T. timopheevii* wheat group contains two tetraploid species: wild *T. araraticum* (syn. *T. timopheevii* Zhuk. ssp. *armeniicum* (Jakubz.) van Slageren) and domesticated *T. timopheevii* Zhuk. ssp. *timopheevii*. Cultivated Timopheev’s wheat was first identified by Russian botanist P.M. Zhukovsky in Georgia in 1922 (Zhukovsky 1928) and is considered a narrowly endemic species, with cultivation documented in only a few

villages of western Georgia (Badaeva et al. 2022). Grown as a ‘maslin’ crop known locally as ‘Zanduri’, *T. timopheevii* was mixed in varying proportions with einkorn wheat (Dekaprevelich and Menabde 1932). Wild *T. araraticum* was first collected by M.G. Tumanyan and A.G. Araratyan in 1925–28 in Armenia and has a broader distribution, with specimens recorded across Transcaucasia and in parts of Iran, Iraq, Syria and Turkey (Badaeva et al. 2022).

Despite recent cultivation of Timopheev’s wheat not being known outside western Georgia, NGW has been recorded as a crop at a range of sites across Europe and Western Asia (Fig. 1; Table 1), dating from the Neolithic–Bronze Age and possibly into the Iron Age (Kenéz et al. 2014). In some cases, remains initially identified as ‘atypical’ emmer wheat were subsequently reassessed in the light of the newly characterised NGW class, such as the chaff recovered at Cafer Höyük, Turkey (Jones et al. 2000). Chiefly these identifications have been based on chaff remains, and while some morphological criteria of NGW grains have been published (Kohler-Schneider 2003), distinguishing the grains, particularly from those of emmer, has been noted as difficult (Valamoti 2017).

Abbreviations: NGW, New glume wheat; GMM, Geometric Morphometrics.

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The relationship between the narrowly endemic modern Timopheev's wheat and the widespread archaeological NGW is uncertain. It is possible that the small population in Georgia is a relic of a formerly much wider cultivated crop. aDNA analysis of Neolithic NGW grains from Çatalhöyük and Miechowiec 4, Poland (Czajkowska et al. 2020) has identified the presence of the G genome, indicating that NGW is a member of the Timopheevii section of wheats, distinct from other polyploid wheats which carry the B genome (Fig. 2). The Timopheevii section contains tetraploid wild and domesticated Timopheev's wheat and the hexaploid wheat *T. zhukovskyi* Menabde & Ericzjan (Badaeva et al., 2022). The presence of the G genome does not, therefore, in itself provide a precise identification.

The aDNA findings also do not preclude the possibility of a separate domestication event having led to a wheat form related, but not ancestor to, modern Timopheev's wheat. Indeed, wheats sharing a genomic constitution may differ significantly in form and function; for example, spelt and bread wheat are both 'BBAADD' hexaploid wheats, but have quite different processing requirements and culinary qualities. Furthermore, recent DNA analysis (Badaeva et al., 2022) has highlighted two distinct lineages of wild *Triticum araraticum*, with the authors positing potential hybridisation between Timopheev's wheats and wild emmer. These insights lend weight to the possibility of multiple evolutionary pathways within the *T. timopheevii* group.

1.2. NGW at Çatalhöyük

A substantial body of Neolithic NGW remains have been recovered from Çatalhöyük, the archaeobotanical dataset of which is currently the largest available for an early farming community in western Asia (Bogaard et al. 2021b). The remains analysed in this study were recovered from the Neolithic East Mound dating 7100–5950 cal. BC. Within Turkey, the Çatalhöyük NGW remains are predated by NGW finds from the mid-9th millennium BC at Aşıklı Höyük (Ergun et al. 2018) and by two spikelet forks of the late 9th–early 8th millennium BC at Boncuklu Höyük (Baird et al. 2018). Spikelet bases at Cafer Höyük dating from the late 9th millennium BC and described as 'machaoïd' emmer also appear to match the morphological characteristics of NGW, not yet characterised at the time of their identification (de Moulins 1993; Jones et al. 2000).

From the earliest levels, a diverse range of cereal and pulse crops as well as wild food-plants are present at Çatalhöyük (Bogaard et al. 2017, 2021b). In early phases NGW is present but as a minor component only, with emmer (*Triticum turgidum* L. ssp. *dicoccum* (Schrunk) Thell.) the dominant wheat crop. The earliest concentrated deposits of NGW were identified in neighbouring buildings of the mid-sequence phase 'North G', and it is not until the Late phase that we see concentrations in the South Area and the emergence of NGW as the most prevalent wheat crop (Bogaard et al. 2021b).

Emmer and NGW are both glume (or hulled) wheats. The ears of glume wheats are formed with a semi-brittle rachis, which when threshed break up into spikelets. These spikelets require further dehulling by pounding to release the grain from the tough glumes (Hillman 1984). In contrast, the rachis of 'free-threshing' wheats is thickened throughout, non-brittle and spikelets remain attached to the intact rachis. The glumes are thinner and the grains are easily released during threshing. Sample compositions indicate that, despite both being glume wheats with the same processing requirements, NGW and emmer were stored, and likely grown, separately, rather than as a mixed crop (Bogaard et al. 2017). Isotopic evidence (Vaiglova 2016; Stroud et al. 2021) and weed functional ecological analysis (Green et al. 2018) suggest that NGW was grown under similarly variable conditions to emmer. Therefore, rather than being environmentally-determined, adoption of NGW is interpreted as an example of household-level experimentation with an existing minor crop potentially relating to group-identity, culture and/or culinary preference (Bogaard et al. 2017, 2021b).

1.3. Archaeobotanical wheat grains and geometric morphometrics

In this study, modern and archaeological glume wheat grains are analysed and compared using geometric morphometrics (GMM). Archaeobotanical wheats grains can be challenging to identify with precision based on traditional morphological criteria (Jones 1998). Grains are usually preserved through charring but are distorted as a result, surviving in identifiable form only when charred within a narrow temperature range under low oxygen conditions (Charles et al. 2015). Charring aside, there is difficulty simply in establishing reliable characteristics by which to distinguish between taxa (Hillman et al. 1996). GMM offers new ways to approach these challenges of characterisation,

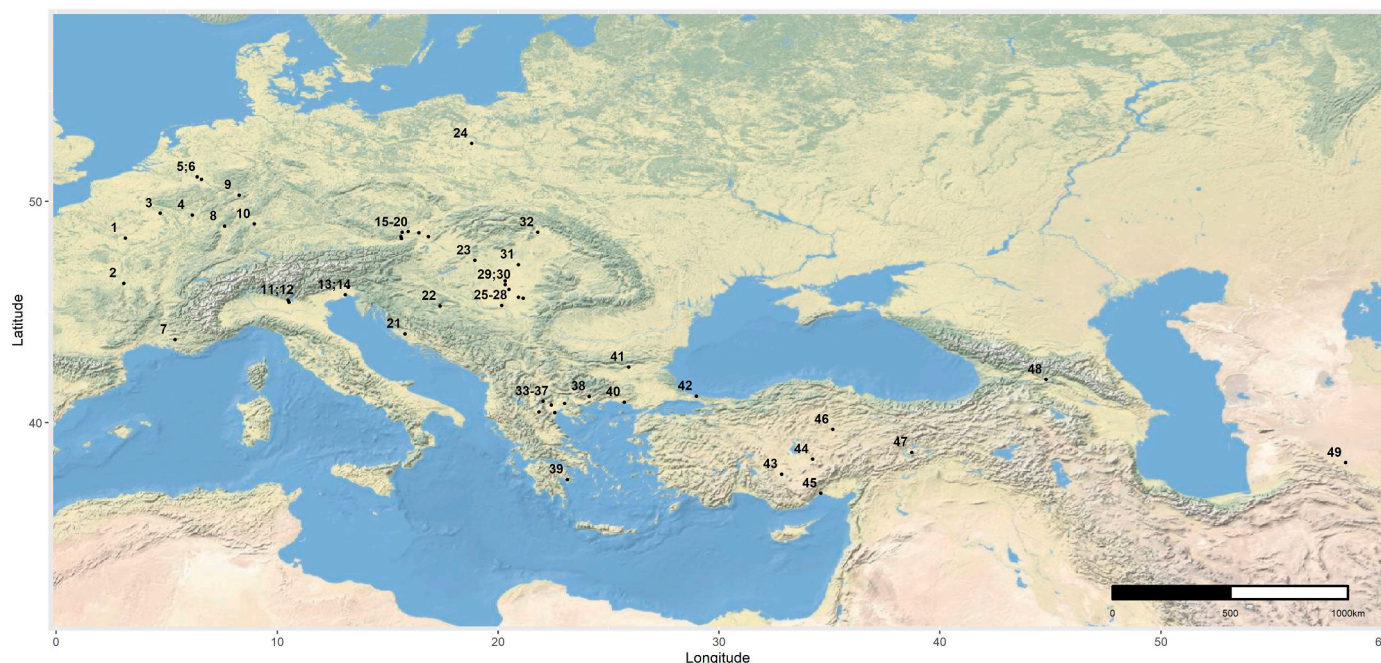


Fig. 1. Distribution map of NGW finds (see Table 1 for key).

with the potential to enhance descriptions of form variation and improve consistency of classifications.

Morphometrics is the application of statistical analyses to size and shape variables, enabling analysis of form in a comparable way to numeric data. In traditional morphometrics, multivariate statistics are applied to a predetermined set of variables, usually consisting of individually measured distances on an organism (Rohlf and Marcus 1993). The development of modern GMM and a suite of new techniques in the 1980s now allows us to analyse shapes as a whole (Adams et al. 2004). The accessibility of these methods has been vastly improved through the development and publication of functions in R (Claude 2008), the open software environment for statistical computing and graphics.

Within archaeobotany, GMM has been successfully applied to the study of grape seeds (Terral et al. 2010; Pagnoux et al. 2015), date palm stones (Terral et al. 2012) and olive stones (Terral et al. 2004; Newton et al. 2006, 2014). Previous studies of archaeobotanical cereals include that by Ros et al. (2014), in which GMM was used to identify two- and six-row barley from Roman contexts in southern France. Bonhomme et al. (2017) established the potential of GMM to distinguish between einkorn, emmer and barley grains before and after charring, further suggesting the potential for intra-species distinction. Wallace et al.

(2018) expanded on these findings, using GMM to distinguish 'bere' barley grains from other British and Scandinavian landraces. Building on these studies, the potential of GMM in relation to morphologically-similar classes of glume wheats of different domestication statuses is explored here for the first time. Methodological uncertainties are also addressed in seeking to quantify which photographic views best allow us to distinguish between wheat types.

2. Methodology

The GMM analysis comprised four stages and is followed by a summary and update of results from a parallel chaff dehiscence study (Charles et al. 2021).

1. Testing the potential for GMM to distinguish between grains of modern glume wheat species.
2. Comparing archaeobotanical glume wheat grains from Çatalhöyük with modern reference material.
3. Analysing chronological changes in the morphology of the Çatalhöyük glume wheat grains

Table 1

Site names and references for NGW distribution map Fig. 1.

Fig. 1 key	Site Name	Country	References
1	Upper Seine Valley (multiple sites)	France	Toulemonde et al. (2015)
2	Petit Beaulieu	France	Toulemonde et al. (2015)
3	Vouziers	France	Toulemonde et al. (2015)
4	Hettange-Grande	France	Toulemonde et al. (2015)
5	Wanlo	Germany	Knörzer (1980); cited Jones et al. (2000)
6	Bedburg	Germany	Knörzer (1974); cited Jones et al. (2000)
7	Pié Fouquet	France	Toulemonde et al. (2015)
8	Gingsheim	France	Toulemonde et al. (2015)
9	Bad Camberg-Würges	Germany	Kreuz et al. (2005)
10	Vaihingen	Germany	Bogaard (2011)
11	Lucene	Italy	Perego (2015)
12	Lavagnone	Italy	Perego (2015)
13	Piancada	Italy	Rottoli and Castiglioni (2009)
14	Sammarinchia/Pavia di Udine	Italy	Rottoli and Castiglioni (2009)
15	Kamegg	Austria	Link (2004); cited Kenéz et al. (2014)
16 (/17)	Krems/Hundssteig	Austria	Kohler-Schneider and Caneppele (2009)
18	Sandberg	Austria	Caneppele et al. (2010)
19	Michelstetten	Austria	Kohler-Schneider and Heiss (2010)
20	Stillfried	Austria	Kohler-Schneider (2003)
21	Velištak	Croatia	Reed and Podrug (2016)
22	Slavča	Croatia	Reed (2017)
23	Százhalombatta-Földvár	Hungary	Stika and Heiss, 2012/3
24	Kujawy District	Poland	Bieniek (2007); Bieniek (2002)
25	Feudvar	Serbia	Borojevic (1991) cited Kohler-Schneider (2003); Reed (2016)
26	Dudeştii Vechi	Romania	Fischer and Rösch (2004)
27	Uivar	Romania	Fischer and Rösch (2004)
28	Parța	Romania	Fischer and Rösch (2004)
29	Hódmezővásárhely	Hungary	Kenéz et al. (2014)
30	Klara Falva	Hungary	Kohler-Schneider (2003)
31	Ecsegfalva	Hungary	Bogaard et al. (2007)
32	Brehov-Pod	Slovakia	Hajnalova (2007)
33	Apsalos	Greece	Valamoti (2017)
34	Giannitsa	Greece	Valamoti and Kotsakis (2007)
35	Kleitos-Kremasti	Greece	Valamoti (2017)
36	Makriyalos	Greece	Jones et al. (2000)
37	Assiros Toumba	Greece	Jones et al. (2000)
38	Arkadikos	Greece	Jones et al. (2000)
39	Franchthi Cave	Greece	Hansen (1991) cited Jones et al. (2000)
40	Makri	Greece	Jones et al. (2000)
41	Karanovo	Bulgaria	Kreuz et al. (2005)
42	Yenikapı	Turkey	Ulaş and Fiorentino (2021)
43	Boncuklu/Çatalhöyük	Turkey	Baird et al. (2018); Bogaard et al. (2013), 2017
44	Aşıklı Höyük	Turkey	Ergun et al. (2018)
45	Mersin-Yumuktepe	Turkey	Ulaş and Fiorentino (2021)
46	Çadır Höyük	Turkey	von Baeyer et al. (2021)
47	Cafer Höyük	Turkey	de Moulins (1993) cited Jones et al. (2000)
48	Atskouri	Georgia	Kenéz et al. (2014)
49	Jeitun	Turkmenistan	Charles and Bogaard (2010)

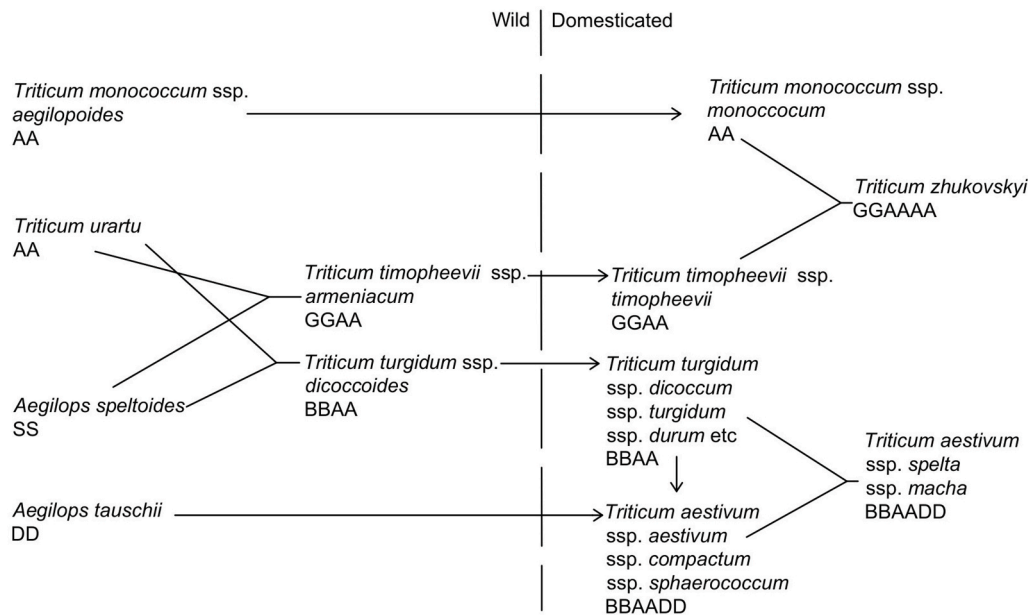


Fig. 2. Simplified genetic diagram showing relationships between wheat species after Li and Gill (2006).

4. Assessing the morphology of Çatalhöyük glume wheat grains as relating to processing stage

2.1. Approach

Because the form of a cereal grain is broadly ‘continuous’, the GMM methodology comprised a type of outline analysis, as opposed to a landmark-configuration approach dependent upon strongly-defined homologous points between individuals (Bonhomme et al. 2014). Here a set of points are still used to describe the shapes and ‘landmarks’ to align them, but the analysis assumes a closed outline in which the form is roughly circular or displays strong bilateral symmetry.

The outline analysis uses ‘Fourier Series’, which approach shapes as periodic functions, decomposing outlines into a series of harmonic sums of trigonometric functions weighted with harmonic coefficients (Bonhomme et al. 2014). The specific technique utilised is Elliptic Fourier Analysis (Giardina and Kuhl 1977; Kuhl and Giardina 1982) which has the advantage of not requiring equally spaced points and allowing for virtually any outline to be fitted (Bonhomme et al. 2014). It is applied using the package ‘Momocs’ (1.2.9) in R (3.6.2), as developed by Vincent Bonhomme, based on functions published by Claude (2008).

To establish a basis of comparison for the archaeological wheat grains, the outlines of multiple accessions of modern wheat grains were captured. Modern grains were photographed before and after charring, with charring conditions designed to replicate well-preserved archaeological material. Photographs were digitised and aligned before extraction into Momocs. The same procedure (minus charring) was applied to the archaeobotanical grains.

2.2. Sampling and photography

Modern reference material was acquired primarily through gene banks with multiple ears used to assess variation within and between accessions. To account for in-ear variation, accessions for which whole ears could be obtained were prioritised, as were those from geographically proximate locations to Çatalhöyük. Grains were sampled from the base, middle and top of the ear with row number and spikelet position recorded. Where whole ears could not be obtained – e.g. as with wild forms which typically shatter before harvest – ear position was reconstructed by counting vascular bundles to procure an equivalent sample

(after Whingwiri et al. 1981).

The final comparative dataset of modern material consisted of 438 grains (Table 2), with the primary dataset comprised of wild and domesticated emmer and Timopheev’s wheat. Part-way through analysis it was observed that archaeological ‘two-grained einkorn’ (*Triticum monococcum* ssp. *monococcum* L.) was similar in appearance to modern *T. araraticum*. Therefore, reference specimens of two-grained einkorn were added to the dataset. As direct comparability of the (potentially environmentally-influenced) modern two-grained einkorn and the archaeologically-observed form remains uncertain (Kreuz and Boenke 2002), this category was represented by modern accessions (Table 2) supplemented by five well-preserved, securely-identified grains from Neolithic Vaihingen, Germany (Bogaard 2011), numbering 38 grains in total. This category was added primarily to prevent misidentification between NGW and two-grain einkorn. However, as relatively limited quantities of material were available, a more systematic analysis of this wheat type would be desirable in the future.

Archaeological grains were selected based on preservation, with those exhibiting clear distortion or damage excluded. Observed signs of distortion resulting from high charring temperatures included protrusions resulting from endosperm exudation, severe blistering of pericarp and large cavities within the grain (Charles et al. 2015). Abraded grains for which there was little or no survival of the outer pericarp were also excluded.

Grains were photographed in dorsal, lateral and polar view (Fig. 3) using a Nikon SMZ25 stereo microscope with an apochromatic optical system and Pixelink M12BC-CYL microscopy camera.

2.3. Charring

Modern grains were charred to replicate well-preserved archaeological material after Charles et al. (2015). Grains were individually wrapped in foil and buried in beakers of sand to reduce oxygen availability. The beakers were then placed in a preheated oven at 230 °C for 6 h. Temperature was monitored using thermacouples and a datalogger to ensure a consistent temperature was maintained throughout.

Table 2

List of modern accessions used as comparative material for GMM analysis. ‘In gl.’ = in glume. * = used for Stage 1 analysis. In addition, five securely identified 2-grain einkorn grains from Vaihingen were included to a total comparative dataset of 443 grains.

Subspecies	Common name	Source	Accession	Origin	No. grains
<i>monococcum</i>	Einkorn (2-grain form)	Berzsenyi College	FOT145142	Romania	26
<i>monococcum</i>	Einkorn (2-grain form)	Mark Nesbitt (Kew)	RMN7537	Unknown	7
<i>araraticum</i>	Wild timopheev's	Gatersleben	TRI11509	Iran	27* (+27 in gl.)
<i>araraticum</i>	Wild timopheev's	John Innes	1150001	Azerbaijan	27*
<i>araraticum</i>	Wild timopheev's	John Innes	1150003	Unknown	27*
<i>timopheevii</i>	Domestic. timopheev's	John Innes	T1160001	Georgia	27*
<i>timopheevii</i>	Domestic. timopheev's	Gatersleben	TRI677	Soviet Union	27* (+27 in gl.)
<i>timopheevii</i>	Domestic. timopheev's	CGN Wageningen	CGN10497	Soviet Union	27*
<i>dicoccoides</i>	Wild emmer	Gatersleben	TRI11501	Turkey	27*
<i>dicoccoides</i>	Wild emmer	Gatersleben	TRI11502	Turkey	27*
<i>dicoccoides</i>	Wild emmer	Gatersleben	TRI16629	Israel	27*
<i>dicoccum</i>	Domestic. emmer	John Innes	1070018	Georgia	27*
<i>dicoccum</i>	Domestic. emmer	Gatersleben	TRI17251	Switzerland	27* (+27 in gl.)
<i>dicoccum</i>	Domestic. emmer	USDA	PI434999	Bosnia & Herzegovina	27*



Fig. 3. Dorsal, lateral and polar views of a grain of domesticated Timopheev's wheat, traced and with alignment points added.

2.4. Digitisation

Grain outlines were traced and aligned using AutoCAD, a design and drafting program. Embryos were excluded as these neither consistently remain attached, nor are likely to be equally developed across specimens (Fig. 3). After Bonhomme et al. (2017), polar views were flipped to face

the same direction to account for the strong bilateral asymmetry often exhibited. Coordinates of outlines were then extracted and saved as .txt files, which take up little file space, can be easily shared and avoid loss of resolution.

The number of coordinate points per outline varied between 35 and 80. Comparison with outlines using a wider range (25–155 points)

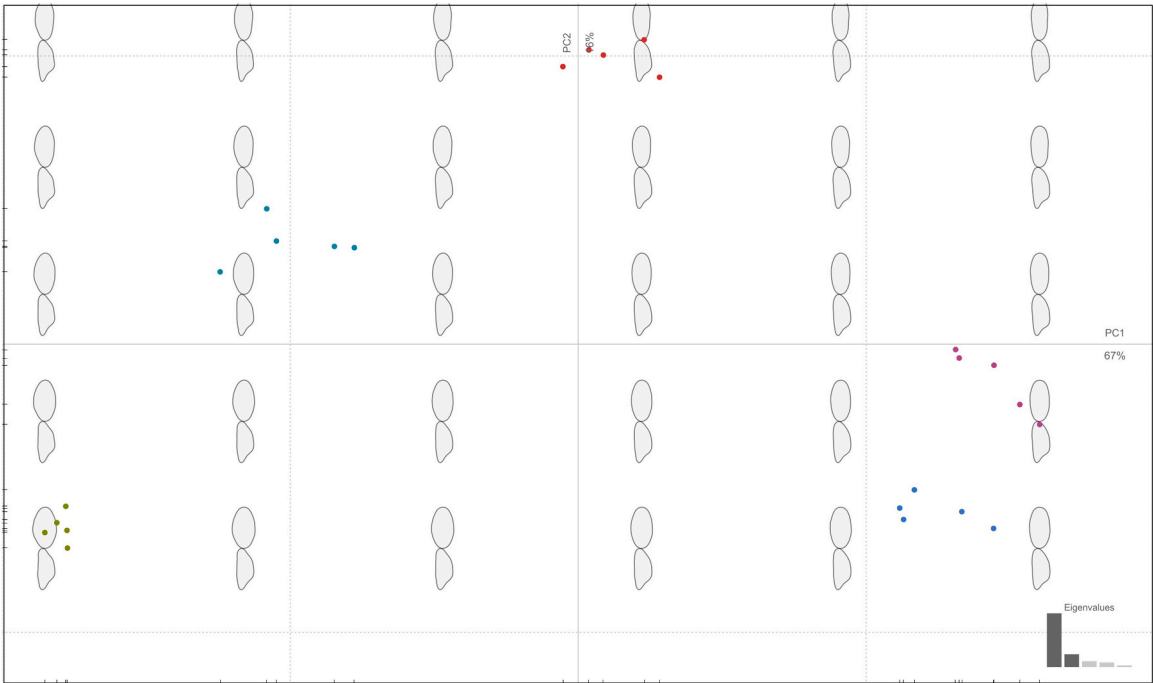


Fig. 4. PCA results of combined dorsal and lateral views when five grains from the same accession were each photographed and digitised five times (each colour = one specimen).

affected reclassification rates by <1%, suggesting the method is not sensitive to the precise number of points used. Repeatability was tested after Evin et al., (2020, 3–4), whereby five grains of the same species were each photographed and digitised five times in five separate sessions. When a principal components analysis (PCA) was performed on combined dorsal and lateral outlines (see Section 3, Stage 1, below) it produced clustering by specimen, although some variation was noted (Fig. 4). Measurement error was calculated after Claude (2008, 65), using Procrustes ANOVA of PCA scores, as 12.51% for the dorsal view and 9.55% for the lateral view. In both views, ANOVA produced significant scores ($p = 0.001$) when specimen was used as an independent variable, and non-significant scores (0.999–1.000) when session was used. This suggests the five sessions did not produce significantly different sets of grain shapes and that variation between session was less significant than variation between specimens.

2.5. Analysis

Once imported into Momocs, outlines were scaled by centroid size to focus the analysis on shape differences. After Bonhomme et al. (2017), Elliptical Fourier Transforms were calculated for the outlines of each grain view individually, before being combined. Eight harmonics were retained for each view, gathering at least 99% of the total harmonic power. In Elliptic Fourier Analysis four coefficients per harmonic are obtained and multivariate analyses can then be performed on these Fourier coefficients (Bonhomme et al. 2014, 8).

Both principal components analysis (PCA) and linear discriminant analysis (LDA) were performed on the transforms, with the former allowing for visual exploration of the data including spotting alignment errors. LDA with leave-one-out cross-validation was used to test the extent to which grains which could be correctly reclassified by species, scoring each known species ('actual') against its designation using the model ('classified'). When archaeobotanical material was introduced as an unknown category, the LDA classified it according to the known type it most closely resembled. When plotted, the LDA uses known class data (e.g. species) to visualise the maximum possible separation based on morphology. When archaeobotanical material is introduced, the plot indicates where the material most closely aligns on the modern spectrum.

3. Results

The following results were generated using data available under supplementary material folders 'GrainCoordinates' (.txt grain outlines), 'GrainDataFrames' (associated.csv files) and 'Classification Files' (summaries of classifications), together with the accompanying R script (<https://github.com/TinaRoushan/New-Glume-Wheat-Geometric-Morphometrics>).

3.1. Stage 1: modern baseline study

Grains of wild and domesticated Timopheev's wheat (hereafter '*T. araraticum*' and '*T. timopheevii*') and domesticated emmer wheat ('*T. dicoccum*') were compared, to establish whether GMM could accurately reclassify them as the correct species and which photographic views were most useful in doing so. A total of 81 grains were used per species from nine accessions in total (Table 2).

Pre-charring, reclassification by species was almost perfect at 99.2% (Table 3). These rates decreased slightly after charring, with dorsal and lateral views in combination correctly reclassifying at 96.3% (Table 4), a slightly higher score than when all three views were used. Regardless of charring status, the polar proved the least useful single view, while the lateral view produced the highest scores when used alone (Tables 3 and 4). The polar view is seemingly not only the least diagnostic pre-charring, but also distorts more than other views during charring. It was therefore concluded that there was strong justification to exclude

Table 3

Results of LDA showing percentage of modern grains correctly classified by species before and after charring when different photographic views used. Highest scores before and after charring are in bold.

View	Uncharred reclassification rate (%)	Charred reclassification rate (%)
Dorsal	90.9	83.1
Lateral	97.5	94.2
Polar	72.4	60.5
Dorsal and lateral	99.2	96.3
Dorsal and polar	95.5	88.5
Lateral and polar	98.8	94.2
Dorsal, lateral and polar	99.2	95.1

Table 4

Results of LDA showing percentage of modern grains correctly classified by species after charring when dorsal and lateral views used in combination.

	Classified as		
Actual	<i>T. araraticum</i>	<i>T. dicoccum</i>	<i>T. timopheevii</i>
<i>T. araraticum</i>	78	0	3
<i>T. dicoccum</i>	0	79	2
<i>T. timopheevii</i>	1	3	77
Class correctness	96.3%	97.5%	95.1%
Leave-one-out cross validation	96.3% (234/243)		

this view from further analyses.

Subsequently, the modern dataset was expanded using dorsal and lateral views of an equivalent sample of wild emmer grains (*Triticum turgidum* ssp. *dicoccoides* (Körn. ex Asch. & Graebn.) Thell.; Table 2). With this addition, separation between species after charring remained robust (Fig. 5), with reclassification rates reducing only slightly to 95.4%.

This stage of analysis was able to confirm the ability of the GMM model to distinguish between charred grains of wild/domesticated emmer and Timopheev's wheat to a high level of accuracy. The highest reclassification rates were achieved when the dorsal and lateral views were used in combination.

3.2. Stage 2: comparison with archaeobotanical material from Çatalhöyük

Dorsal and lateral views of well-preserved emmer and NGW grains from a range of East Mound contexts were subsequently compared with the modern wheat grains.

Initially, 86 archaeological grains confidently identified from 'pure deposits' of either emmer or NGW (Appendix A) were added to the LDA as separate named categories, alongside the known modern types analysed above and the smaller sample of two-grain einkorn. It was observed that the grains plotted as two distinct groups: archaeological emmer overlapping with modern emmer and NGW plotting between wild and domesticated Timopheev's wheat (Fig. 6). These results support the morphological affinity between NGW and Timopheev's wheat as previously observed in chaff remains (Jones et al. 2000).

To expand the dataset, archaeological grains from less certain 'mixed' deposits (i.e. containing more than one type of wheat identification) were then added as an unknown category for reclassification. Based on the LDA, they were assigned as either emmer, NGW or excluded (e.g. if classified as 'two-grained einkorn'; see supplementary data for further details). The aim of this approach was to not allow the original archaeobotanical identification of a grain to pre-determine the assigned category, but rather to rely on the GMM model. As a result, numerous grains of uncertain classification (e.g. labelled 'emmer/NGW') could be identified, while a few grains were reassigned to different species.

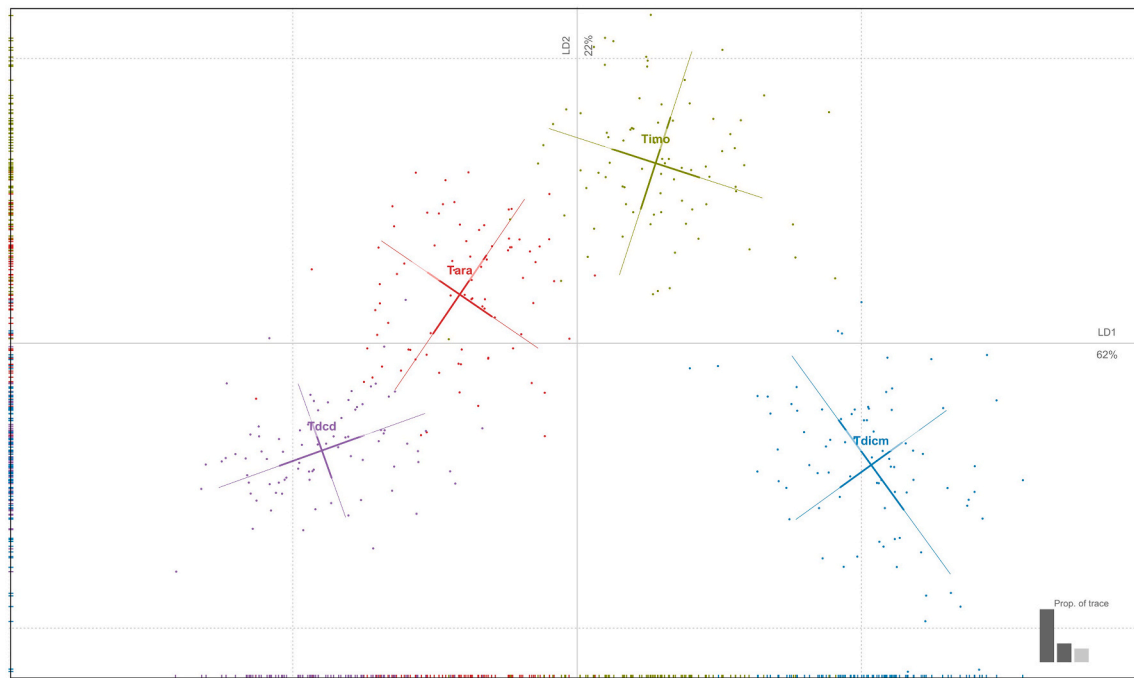


Fig. 5. LDA results showing separation of modern glume wheat species based on grain shape ('Tdcdd' = *T. dicoccoides*, 'Tara' = *T. araraticum*, 'Timo' = *T. timopheevii*, 'Tdicm' = *T. dicoccum*).

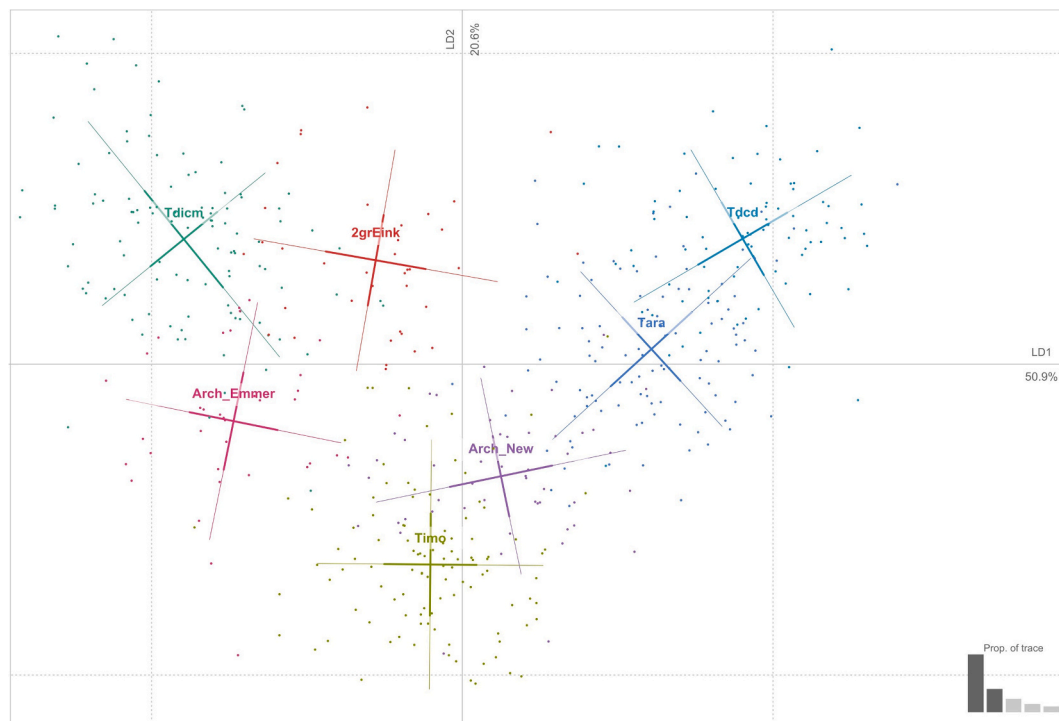


Fig. 6. LDA showing relationship of archaeological emmer ('Arch_Emmer') and NGW ('Arch_New') grains from 'pure' deposits to comparative dataset of glume wheats. NGW grains are positioned between wild ('Tara') and domesticated ('Timo') Timopheev's wheat. ('Tdicm' = *T. dicoccum*, '2grEink' = two-grained einkorn, 'Tdcdd' = *T. dicoccoides*).

The final dataset contained 443 grains of comparative material (Table 2) and 231 Çatalhöyük grains identified as emmer or NGW, combining both grains from 'pure deposits' and those identified in comparison with these using GMM analysis, from a total of 60 contexts (Appendix A). This dataset was then used to conduct analyses by phase and relating to processing stage.

3.3. Stage 3: analysis by phase

Archaeological grains were subsequently coded by chronological phases as defined in Hodder, (2021, 11): Early (7100–6700 cal. BC), Middle (6700–6500 cal. BC) and Late(Final) (6500–5950 cal. BC).

This time, the LDA showed that NGW grains from the Early phase

plotted more closely to wild Timopheev's wheat and over time plot increasingly closely to domesticated Timopheev's wheat, with the most significant shift apparent between Early and Middle phases (Fig. 7). When archaeological emmer grains were coded by phase no such pattern was apparent.

NGW grains were then entered as 'unknowns' into an LDA using wild and domesticated Timopheev's wheat as classifiers. In the Early phase 57.1% of NGW grains classified as wild, decreasing to 20.4% by the Late phase (Table 5). A chi-squared test on the classifications produced p-values of <0.05 when comparing Early with Middle and Late phases, but produced a value of 0.3654 when Middle and Late phases were compared. This gives confidence in a significant shift between Early and Middle phases towards the domesticated form, if not between Middle and Late phases.

Comparing stacked outlines of NGW grains across phases revealed only subtle changes (Fig. 8). In the lateral view, dorsal curvature becomes slightly more pronounced, with the widest point of the grain shifting towards its apex. In the dorsal view, the widest point of the grain shifts slightly in the same direction, particularly in the Middle phase. Potentially these changes are concentrated towards the top of the grain because it is less tightly constrained by the glumes. These outlines provide useful identification criteria for NGW grains in line with those reported by Kohler-Schneider (2003), including a 'rather rounded apex' and dorsal edge running more parallel to the ventral than emmer when viewed laterally (Fig. 9).

Grain size was also measured, taking length and width in the dorsal view and depth in the lateral (after Charles et al. 2021). Between the Early and the Middle phase all three average NGW measurements increased, decreasing very slightly in the Late phase. For the emmer grains the largest measurements are from the Early phase with no clear differentiation between Middle and Late phases (Table 6).

In summary, analysis of both shape and size suggest a shift in NGW grains between Early and Middle phases towards larger grains which more consistently resemble domesticated Timopheev's wheat in shape. This development in form persists into the Late phase, although a small

Table 5

Results of LDA classification when NGW grains entered as unknowns against modern *T. araraticum* and *T. timopheevii* grains and p-values of chi-squared test performed on frequency tables.

Phase	Grains classified as <i>T. araraticum</i>	Percentage classified as <i>T. araraticum</i>
Early	16/28	57.1%
Middle	16/53	30.2%
Late	10/49	20.4%
P-value (all phases)	0.0037	
P-value (early vs mid only)	0.0339	
P-value (mid vs late only)	0.3654	
P-value (early vs mid + late)	0.0032	

size decrease is noted (<0.07 mm in any dimension). In contrast, emmer grains at no stage resemble wild emmer and are well-developed in size from the earliest phase.

3.4. Stage 4: analysis by processing stage

This stage sought to establish whether the archaeological grains were charred within their glumes (i.e. prior to dehusking) or as individual grains. Therefore, the data was recoded to reflect the subset of modern grains charred within their glumes (Table 2) and extracted before photographing.

In the LDA results, both NGW grains and emmer grains consistently plotted more closely to modern 'in glume' grains than those charred individually (Fig. 10), indicating that the archaeobotanical grains more closely resemble grains charred in their glumes. Results suggest a morphological distinction between grains charred, prior to, and after, dehusking, with glume-enclosed grains appearing slightly laterally compressed and 'hunched' in appearance (Fig. 11). Based on the analysis we can propose that the majority of grain at Çatalhöyük came to be

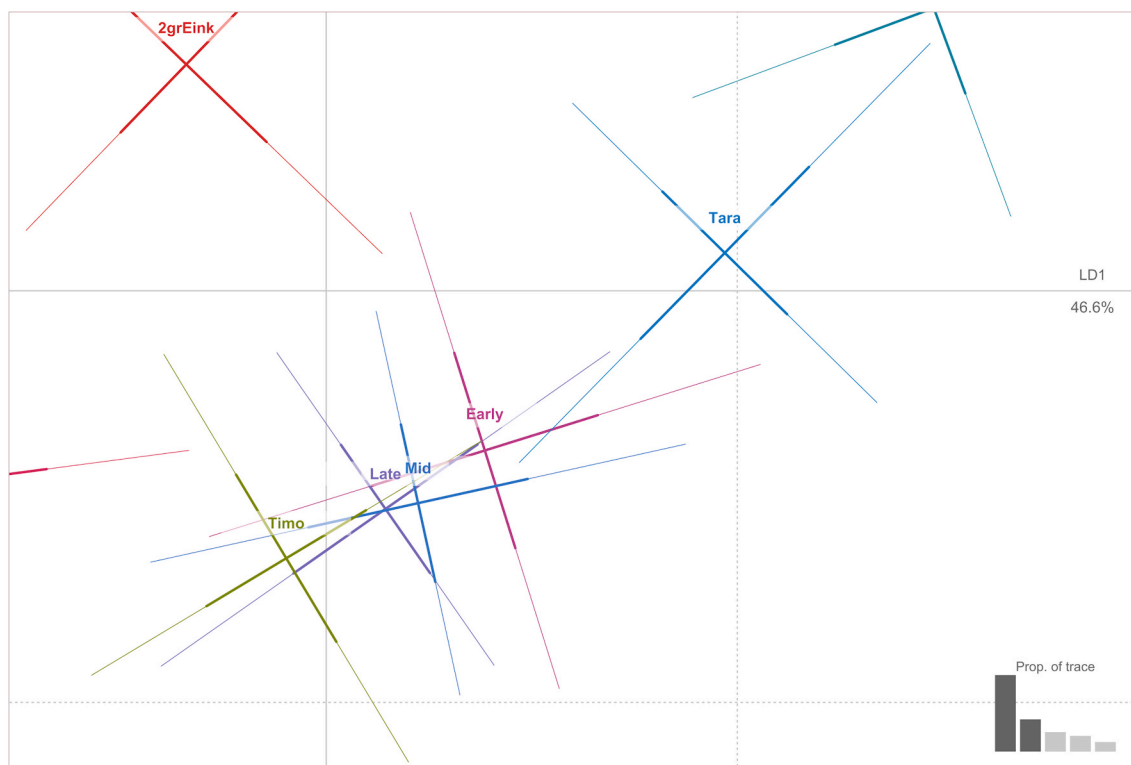


Fig. 7. LDA results when plotted with full dataset and NGW grains recoded as 'Early', 'Mid' and 'Late' phase (Timo = *T. timopheevii*, Tara = *T. araraticum*).

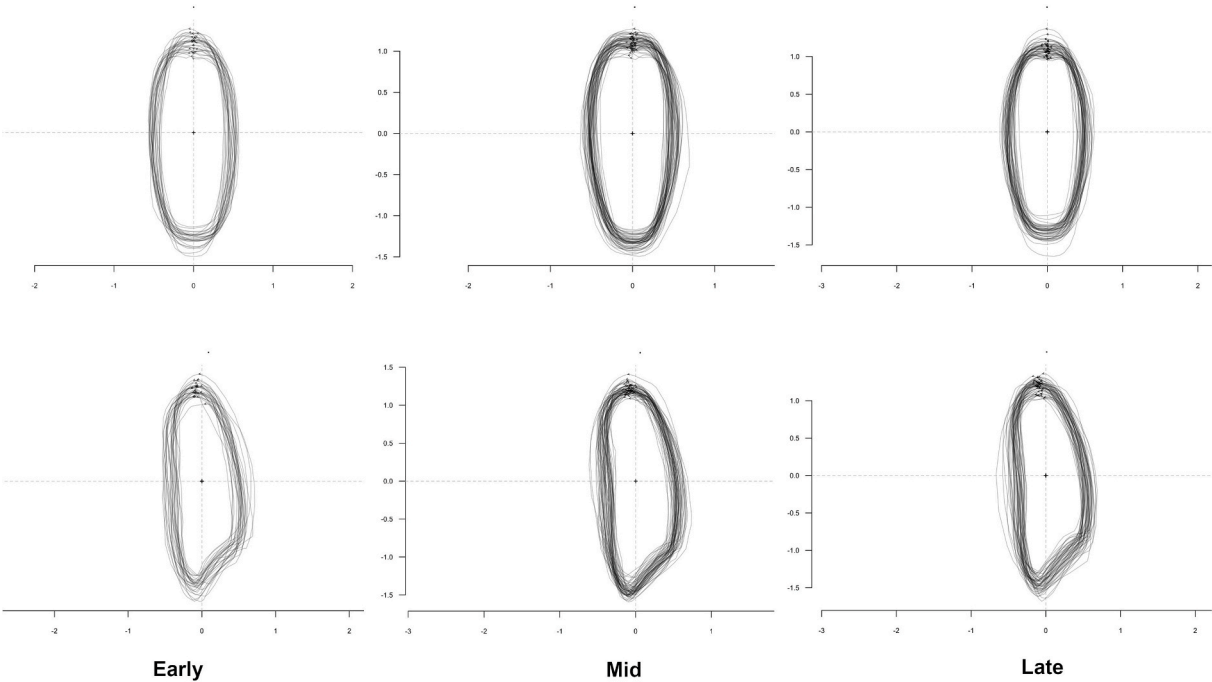


Fig. 8. Stacked outlines of Çatalhöyük NGW grains from Early, Mid and Late phase contexts.

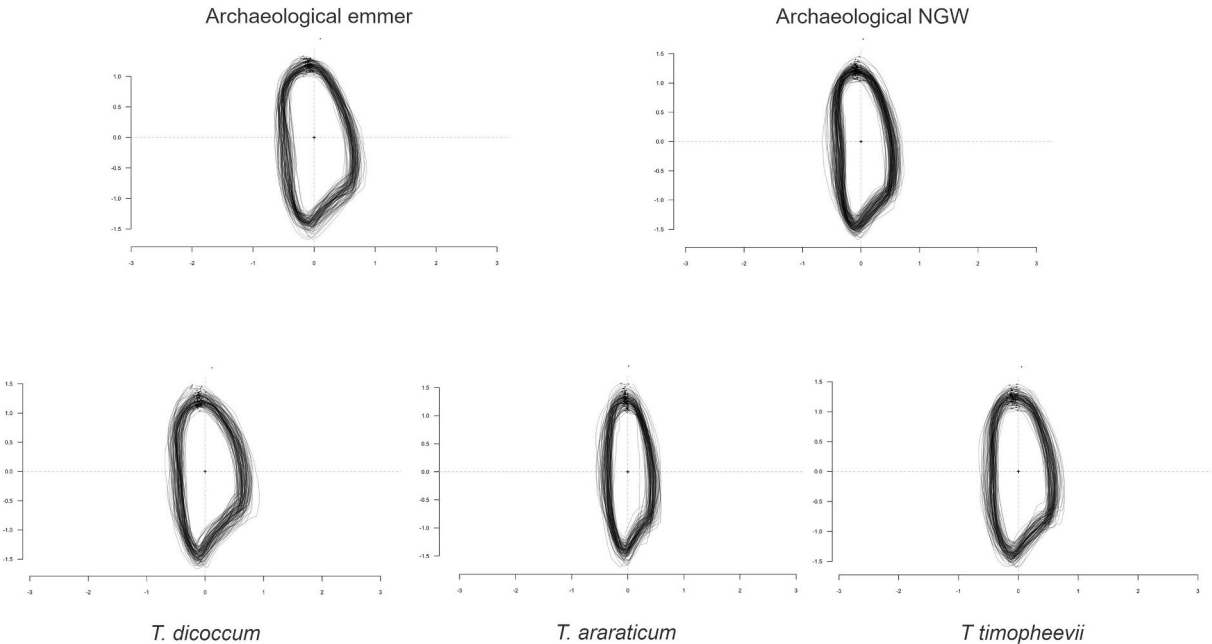


Fig. 9. Stacked outlines of Çatalhöyük emmer and NGW grains (all phases) alongside modern *T. dicoccum*, *T. araraticum* and *T. timopheevii* in lateral view.

Table 6
Average dimensions of Çatalhöyük NGW and emmer grains summarised by phase. Depth = widest point of grain in lateral view.

	Average length (mm)	Average width (mm)	Average depth (mm)
Emmer			
Early	5.8834	2.9028	2.5585
Middle	5.4368	2.8435	2.4745
Late	5.7331	2.8368	2.4556
NGW			
Early	5.3095	2.1425	1.8984
Middle	5.6882	2.4428	2.0626
Late	5.6561	2.3823	2.0520

charred whilst stored in its glume and prior to dehusking; this complements direct evidence of spikelet storage in the form of intact NGW spikelets recovered from Building 77 (Bogaard et al. 2013).

3.5. Assessing dehiscence from chaff morphology

A previous study of NGW chaff remains from Çatalhöyük supports the theory that the crop underwent domestication during the course of the settlement (Charles et al. 2021). This study is summarised here and updated with an increased sample of chaff remains from the Early phase.

The study analysed spikelet bases after Tanno and Willcox (2012), on the basis that domesticated wheats do not ‘shatter’ to distribute their

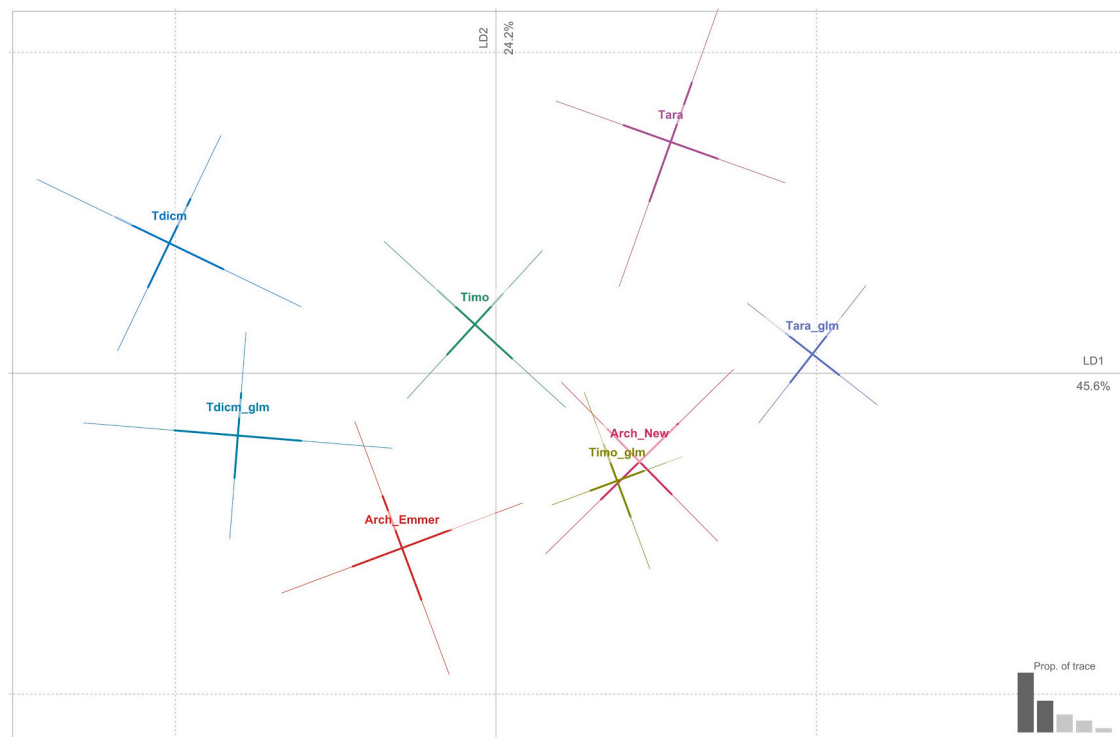


Fig. 10. LDA showing archaeological grains ('Arch_Emmet' and 'Arch_New') plotting more closely to modern grains which were charred in chaff ('_glm'). ('Tdicm' = *T. dicoccum*, 'Timo' = *T. timopheevii*, 'Tara' = *T. araraticum*).

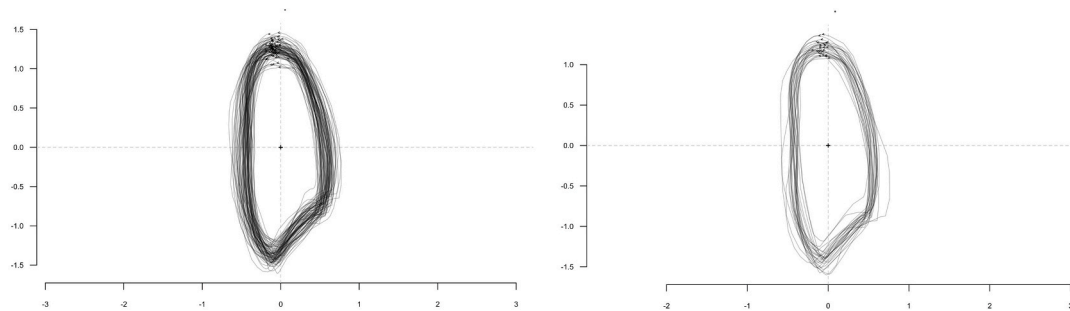


Fig. 11. Stacked outlines of *T. timopheevii* grains when charred as individual grains (left) and when charred within glume/chaff (right).

seeds, i.e. the ear does not disarticulate into individual spikelets upon maturity but needs to be threshed after harvesting. The attachment point of each spikelet (or 'abscission scar') will therefore show signs of tearing, with part of the adjoining rachis segment more likely to remain

attached. Wild forms detach naturally when ripe and the abscission scars are more likely to be smooth (Fig. 12; see also Charles et al. 2021). However, sometimes part of the rachis internode can remain attached to wild forms, and in emmer wheat these can be distinguished by profile

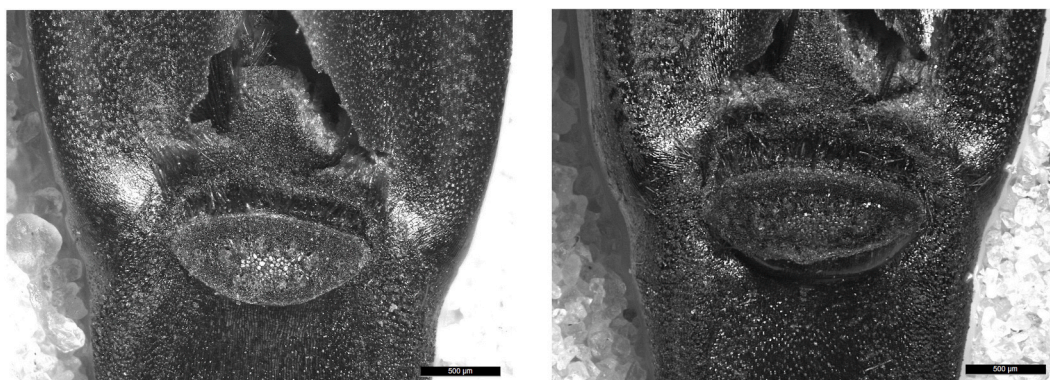


Fig. 12. Abscission scars of *T. araraticum*, showing the more common 'smooth' form (left) and the less common protruding form with tearing visible (right).

(Weide 2015).

Analysis of modern Timopheev's wheat spikelets established that no distinction between wild and domesticated forms could be made based on individual scar profiles. However, there were clear differences in the proportions of scar types, with domesticated populations having a much higher proportion of 'rough' and 'protruding' (with partial rachis segment attached) scars while wild specimens had predominantly 'smooth' scars (Fig. 12). When NGW chaff from Çatalhöyük was examined it was observed that, where the rachis segment remained attached, it exhibited the same profile as in Timopheev's wheats: an abrupt or 'knee-shaped' transition to the upper rachis segment. Furthermore, a clear temporal trend from smoother to rougher scars was observed in the NGW remains, suggesting decreased shattering tendency over time (Fig. 13). Also observed was an increase in 'terminal' spikelets (i.e. from the top of the ear) between the Early and Late phase, significant because these generally detach first in shattering forms. Emmer spikelet bases from Çatalhöyük neither exhibited a comparable trend as regards proportions of 'rough' scars, nor were any spikelets identified which exhibited the 'wild-type' rachis attachment profile described in Weide (2015).

Overall the chaff evidence suggests selection for non-shattering forms in NGW over the course of the East Mound settlement sequence. In comparison, the morphology of emmer wheat as a non-shattering wheat was apparently established prior to the earliest settlement phase.

4. Discussion

4.1. Domestication processes

The GMM grain analysis and parallel chaff study support close comparability of NGW with modern Timopheev's wheats. Moreover, the findings demonstrate changes to grain size/shape and ear shattering behaviour during the East Mound sequence. These changes constitute a shift from remains more closely resembling wild Timopheev's wheat to those more closely resembling the domesticated crop. The developments emerged gradually over a period of 1150 years, prompting consideration of the degree to which these traits were consciously selected by cultivators.

A co-evolutionary approach to domestication considers human-plant interactions as relationships with both intended and unintended consequences (Jones et al. 2021). Niche construction forms part of a broader process of co-evolution in which all organisms actively and continuously participate (Bogaard et al. 2021a). Human interaction with the environment creates specific conditions in which certain functional ecological traits may gain competitive advantage: for example, by modifying growing conditions or acting as dispersal agents. In turn, humans become increasingly dependent on those plants which thrive in anthropogenic environments (Rindos et al. 1980; Rindos 1984).

As regards ear shattering behaviour, selection for decreased

dehiscence continued into the Late phase as the crop was increasingly relied upon as a staple across the settlement. Changes in dehiscence are usually explained in terms of harvesting methods (Charles et al. 2021). Chert and obsidian sickle-type blades are attested from Early phase levels at Çatalhöyük (Carter 2011) and use-wear analysis of blades indicates repeated cutting of cereals, albeit in a limited number of cases (Lemorini and D'Errico 2021). Sickle harvesting, or any harvesting method that recovers the entire ear (as opposed to hand-gathering mature spikelets), gives 'non-shattering' plants a competitive advantage, with seeds from non-shattering plants more likely to be harvested and sown the following year, whilst also enhancing reliability and yield of the crop for humans. However, sickle-harvesting is not the sole mechanism for increasing indehiscence, and annual harvesting and sowing cycles may also exert a gradual influence (or 'weak selection') even when ears are not cut (Maeda et al. 2016) which may over time increasingly encourage the use of sickles.

The gradual pace of change in grain form, and the fact that seed-size by itself is not a predictor of yield (Jones et al. 2021), mean we cannot explain this process purely in terms of human desire to increase harvests. Research has demonstrated that larger seeds of wild crop progenitors are more successful in rich, disturbed anthropogenic environments, germinating more quickly and producing larger seedlings/plants with more robust root systems (Jones et al. 2021). Analysis of arable weed flora suggests that Çatalhöyük crops were grown in tilled and fertile soil (Green et al. 2018), i.e. conditions conducive to selection for larger seeds. As seed size increased, and the plants adapted to these types of conditions, they would become increasingly dependent on human amendment of the soil to thrive. It is therefore likely that both human intervention and environmental selection interacted to produce the developments in NGW at Çatalhöyük, and that the role of human intention was both 'complex and indirect' (Bogaard et al. 2021a, 10).

The observed changes do not represent an entire domestication sequence, as NGW remains from the earliest phase are not entirely 'wild'; rather, a greater proportion more closely resemble wild forms, and these early populations are perhaps best described as 'semi-shattering'. A possible alternate theory is that during periods of early adoption, seed stock of domesticated NGW was bolstered by wild stands (Willcox 2005). However, although wild Timopheev's wheat has been identified in Turkey, these observations are confined to the south-east of the country (Mitrofanova et al. 2016; Badaeva et al., 2022), outside Central Anatolia. While we cannot rule out *T. araraticum* having been present in the region during the Neolithic period, it seems more likely that a partially-domesticated form of the wheat was available from the earliest phases and continued to undergo adaptation during the course of the settlement.

4.2. Incentives for cultivation of NGW

The more widespread cultivation of NGW and its adoption in the

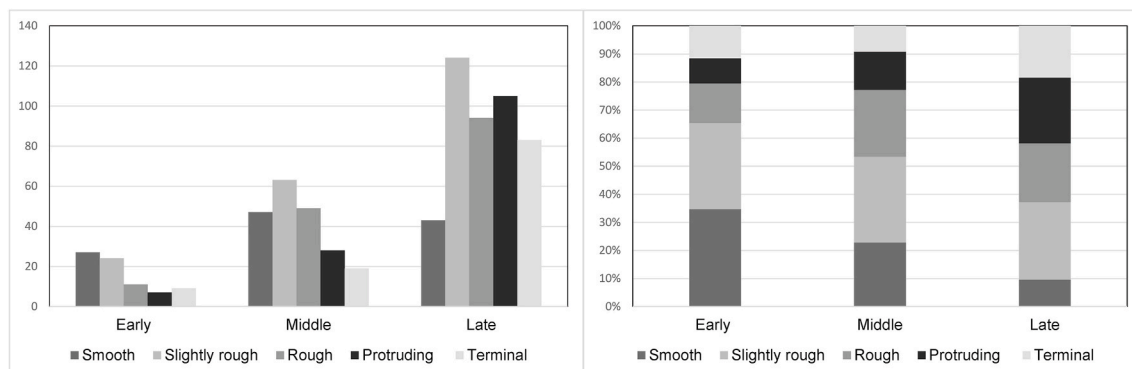


Fig. 13. Number and proportion of different categories of abscission scar types at Çatalhöyük by phase.

South Area by the Late phase coincides with the development of desirable qualities in the crop relating to seed size and shattering. We may, however, question what motivated initial investment in this crop in the North Area — particularly when emmer wheat, a crop with similar processing and environmental requirements was readily available in domesticated form.

The inhabitants of Çatalhöyük had a broad subsistence base of cultivated and gathered food-plants, and experimentation with different resources was potentially a way of buffering risk against individual resource failures (Bogaard et al. 2017). It is therefore possible that cultivating multiple wheat crops was considered ‘less risky’ in the face of potential climate fluctuation or disease. While we cannot be certain of the specific traits of NGW or how they were perceived, modern Timopheev’s wheat possesses significant resistance to fungal diseases including leaf and stem rust (Leonova et al. 2002). Both Turkey and Georgia fall within the region vulnerable to highly damaging wheat rust diseases (Food and Agriculture Organization of the United Nations, 2014), so potentially this resistance was advantageous at Çatalhöyük and/or within the context of its cultivation in the recent past.

Other factors providing more personalised incentives might include the culinary qualities of specific plants and/or their ability to mark social differentiation between households. In Georgia, as part of the maslin ‘Zanduri’, fragile ears of Timopheev’s wheat were harvested using a pair of wooden rods called ‘shnakvi’ (Mitrofanova et al., 2016). The grain was used to make ‘Zanduri bread’ which was associated with special occasions (Jorjadze et al. 2014) and for feeding fowl, while the straw was used for roofing (Mitrofanova et al. 2016). It is possible that while potentially adapted to multiple functions, NGW was also used in specific culinary preparations associated with particular households, other social groupings and/or occasions. Its cultivation may also have been associated with certain tools or practices which marked out its farmers as a distinct group.

5. Conclusion

GMM analysis of NGW grains from Çatalhöyük established a strong morphological similarity with modern Timopheev’s wheat. These findings reinforce links previously made using chaff (Jones et al. 2000) and aDNA (Czajkowska et al. 2020) and we therefore propose that NGW be described in future as *Triticum timopheevii* s.l. (*sensu lato*) (after Badaeva et al., 2022), reserving *T. timopheevii* s. str. (*sensu stricto*) for the narrowly endemic modern form.

Results further demonstrate the potential of GMM to distinguish between charred grains of morphologically-similar wheat species and sub-species of differing domestication status; particularly when the dorsal and lateral views of the grain are used. The method even appears sufficiently sensitive to suggest whether grains were dehusked before storing. Applications of GMM to archaeobotanical studies of wheat therefore seem promising, including at sites where identification of *T. timopheevii* s.l. remains uncertain, or for further studies of the transition between wild and domesticated wheats. Research into refining identifications of free-threshing wheats forms and expanding modern comparative datasets is also currently underway.

At Çatalhöyük, comparison of NGW with modern Timopheev’s wheats suggests that the crop underwent domestication processes during the Neolithic East Mound sequence. In the Early phase a higher proportion of NGW grains resemble wild Timopheev’s wheat and become more similar to the domesticated form over time, accompanied by a size increase. Changes in grain form were most marked between the Early and Middle phases, coinciding with more widespread adoption of the crop in the North Area. Building on previous work (Charles et al. 2021) analysis of NGW chaff morphology also detected a reduction in shattering. This decrease in shattering continued into the Late Phase, by which time the NGW had apparently replaced emmer as the settlement’s main wheat crop. In contrast to NGW, emmer wheat was found to be more fixed in form, being well-developed in both size and non-shattering

properties from the earliest phase.

It is proposed that a partially-domesticated form of NGW was available from the earliest phases and continued to undergo adaptation over the course of the settlement. Sickie harvesting and cultivation in relatively fertile and disturbed soil facilitated a gradual co-evolutionary process whereby both human intervention and environmental conditions selected for mutually beneficial traits of reproduction and yield. The role of human intention in these changes is understood to be ‘complex and indirect’ (Bogaard et al. 2021a, 10) as opposed to a unidirectional process of selection. Possible incentives in the initial uptake of the crop may have included culinary qualities, cultural differentiation between households, its resistance to fungal disease and/or its multi-functional properties. More broadly, investment in the crop may be understood within the context of a broad-spectrum plant strategy (Bogaard et al. 2017), in which risk of individual resource failure was offset by diverse strategies at the household level.

Declaration of competing interest

None.

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Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jas.2022.105599>.

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