Consumption patterns in prehistoric Europe are consistent with modern economic behaviour

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Editor summary:

Prehistoric economic behaviour in Europe fits well with modern economic theory, based on a large database of metal objects from across Europe.

Peer review information:

Nature Human Behaviour thanks Maciej Kasiński and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Inventory of Supporting Information

1. Extended Data

Figure or Table #	Figure/Table title	Filename	Figure/Table Legend
Extended Data Fig. 1	Orders of magnitude	Ext_01.pdf	The boxplots show the distribution of the mass values balance weights pertaining to the *shekel*- and the *mina*-range, compared to the distribution of metal fragments and complete objects. Dotted lines indicate the approximate value of the weight units. Solid lines indicate the boundaries of the CQA sampling (7-200 g). *Shekel*: n=244, min.=0.16 g, max.=469.41 g, centre=9,.77 g, box bottom=4.08 g, box top=32.01 g, whisker bottom=0.16 g, whisker top=100.00 g. Fragments: n=6,881, min.=0.01 g, max.=9,220 g, centre=26.00 g, box bottom=7.90 g, box top=82.00 g, whisker bottom=2.70 g, whisker top=233.00 g. Complete: n=6,746, min.=0.27 g, max.=8,750 g, centre=181.00 g, box bottom=375.27 g, box top=210.00 g, whisker bottom=31.30 g, whisker top=340.00 g. *Mina*: n=367, min.=11.8 g, max.=5,050 g, centre=592.00 g, box bottom=375.27 g, box top=908.30 g, whisker bottom=235.20

			g, whisker top=998.36 g. Outliers method: 1.5*Interquartile range. Graph made with Wavemetrics Igor Pro 6.05.0.
Extended Data Fig. 2	CQA, diachronic results	Ext_02.pdf	Dotted lines represent the raw output of the quantal analysis. Solid lines represent the same output after smoothing. We indicate the number of measurements sub-sampled in each quantogram, and in parentheses the total sample size.
Extended Data Fig. 3	Monte Carlo Simulation	Ext_03.pdf	CQA of the sample of bronze fragments of Phases 2-3 compared to the CQA results for balance weights. Left Y axis: balance weights. Right Y axis: bronze fragments. The horizontal dashed line represents the 5% significance level for the Monte Carlo simulation (ϕ(q)=7.35), lower than the peak value of bronze fragments (ϕ(q)=7.77).
Extended Data Fig. 4	Binned Frequency Distribution Analysis of metal fragments	Ext_04.pdf	Bin size=1.11 g. The dots overlaid on the histograms represent multiples of 10 g (i.e., the approximate value of the Pan-European *shekel*); the boundaries represent a CV=5% at 1 SD. The dots' Y values are arbitrarily placed for visual clarity. Above: Phase 1 (n=397). Below: Phase 2 (n=3,339) and 3 (n=3,145).
Extended Data Fig. 5	Binned Frequency Distribution Analysis of complete metal objects	Ext_05.pdf	Bin size=11.1 g. The dots overlaid on the histograms represent multiples of the theoretical value of Pan-European *shekel* of 10 g; the whiskers represent CV=5% of each of these multiples at 1 SD. The dots' Y values are arbitrarily offset, in order to avoid visual confusion generated by the overlapping error margins. Above: Phase 1 (n=4,558). Below: Phase 2 (n=1,075) and 3 (n=1,113).
Extended Data Fig. 6	One-sample Kolmogorov Smirnov test for normality (two-sided)	Ext_06.pdf	The graphs compare the Cumulative Distribution Functions (CDF) of archaeological datasets and normal distributions. The *p*-values and test statistic *D* of each test are shown on the graphs.
Extended Data Fig. 7	Simulation scenario 2: Monetary fragmentation	Ext_07.pdf	Green area: CI=95% of the simulated results (DDF and Q-Q plots). Green line: mean values of the simulated results (DDF and Q-Q plots). Orange lines: KDE of the distribution of metal

			fragments. Orange dots: Q-Q plots of the distribution of metal fragments.
Extended Data Table. 1	Results of the bootstrapped two-sample Kolmogorov-Smirnov test (two-sided)	Ext_Tab_01.pdf	The test compares the distribution of mass values of each chronological phase with a bootstrapped sampling of the simulatioan results for Scenario 1 – random fragmentation.

1. Supplementary Information:

A. PDF Files

Item	**Present?**	**Filename** **Whole original file name including extension. i.e.: Smith_SI.pdf. The extension must be .pdf**	**A brief, numerical description of file contents.** i.e.: ***Supplementary Figures 1-4, Supplementary Discussion, and Supplementary Tables 1-4.***
Supplementary Information	No		
Reporting Summary	Yes	nr-reporting-summary_new.pdf	
Peer Review Information	Yes	PRFile_Ialongo.pdf	

B. Additional Supplementary Files

Type	**Number**	**Filename**	**Legend or Descriptive Caption**
Supplementary Data	1	SI_01_metal objects.xlsx	Database of the metal objects from Bronze Age hoards considered in this study
Supplementary Data	2	SI_02_balance weights	Database of Bronze Age balance weights

CONSUMPTION PATTERNS IN PREHISTORIC EUROPE ARE CONSISTENT WITH MODERN ECONOMIC BEHAVIOUR

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Abstract

Have humans always sold and purchased things? This seemingly trivial question exposes one of the most conspicuous blind spots in our understanding of cultural evolution: the emergence of what we perceive today as 'modern' economic behaviour. Here we test the hypothesis that consumption patterns in prehistoric Europe (c. 2,300-800 BCE) can be explained by standard economic theory, predicting that everyday expenses are log-normally distributed and correlated to supply, demand and income. Based on a large database of metal objects spanning northern and southern Europe (N=23,711), we identify metal fragments as money, address them as proxies of consumption, and observe that starting c. 1,500 BCE their mass values become log-normally distributed. We simulate two alternative scenarios, and show that: 1) random behaviour cannot produce the distributions observed in the archaeological data, and 2) modern economic behaviour provides the best-fitting model for prehistoric consumption.

INTRODUCTION

Standard microeconomic theory, at its core, assumes that humans will engage in transactions as a means to fulfil their needs and wants[1]. It is, in other words, grounded on the assumption that a particular form of basic behaviour is recurrent and somehow predictable. But is such a behaviour a constant throughout human history, or is it a product of advanced economic systems?

The late prehistory of Europe (c. 2,300-800 BCE) offers an ideal case study for the evolution of economic behaviour in pre-modern economies. The substantial research investment of the last two decades has provided impressive detail on production and trade in the Bronze Age[2]. As a wide range of commodities (such as copper, amber, tin, wool, salt) was in constantly high demand across the continent, regional locales seem to have specialised in the production of single commodities for export[3–8]. Moreover, the idea that money was widespread in late prehistoric Europe is becoming commonplace[9–12], supported by recent studies aimed at its identification[13,14]. Massive production and export are seen as the engines of an exchange economy of continental reach. Regional locales act as firms in maximizing output for gains in line with standard macroeconomic theory[3–5,15], while local elites organise the massive labour input required to sustain the system, and entertain mid-to long distance relationships with peers across the continent to maintain trade routes[15,16].

At a superficial glance, current models might appear to describe Bronze Age Europe as a fully-fledged market economy, if it were not for the conspicuous difference represented by individual agency and consumption patterns: elites unilaterally control production and trade and are the only actors with some sort of entrepreneurial agency, while everyone else is the passive recipient of redistribution mechanisms, and money never plays any active role[15,17]. As a result, things are never ‘sold’ and ‘purchased’ but only generically ‘exchanged’, and the economic agency of the vast majority of individuals – the so-called ‘commoners’[17] – remains virtually invisible[14]. The unbalance between production and consumption, then, is explained by postulating that excess produce was destined to display and ritual destruction, with the ultimate goal of reproducing social systems and reaffirming hierarchies[18–21].

In a way, current models portray an economy in which everyone produces but only very few consume, which, from the perspective of standard economic theory, represents a paradox: simply put, economies are assumed to produce approximately as much as they can consume, and individuals freely engage in transactions proportionately to their economic capacity. It follows that, if we change this assumption, then we can have a different kind of economic theory. Once highly influential[22–24], the notion that economic behaviour in so-called ‘primitive’ economies was substantially ‘other’ than in modern ones is now generally rejected in contemporary economic anthropology[25–29]. It endures, however, in prehistoric archaeology to justify the lack of economic agency outside of elite groups: either implicitly or explicitly, the absence of economic agency is not as much of a consequence, but rather a theoretical precondition for an interpretive model in which the ultimate end of production is not consumption, but rather display and destruction. The supposed ‘otherness’ of prehistoric economic behaviour, however, is only based on conjecture and was never tested empirically.

We test the hypothesis that economic behaviour in prehistoric Europe was not substantially different from modern behaviour, i.e., that prehistoric individuals and households normally engaged in economic transactions to fulfil their needs and wants. We address this hypothesis empirically, and test whether the archaeological evidence is consistent with consumption patterns that are expected in contemporary Western economies. Today, the distribution of transaction values in which households engage in a given period of time (i.e., consumption) tends to follow a log-normal distribution, meaning that average transactions are much smaller and vastly more frequent than very high ones, but only moderately bigger and more frequent than very low ones[30–33]. This reflects the tendency of the vast majority of households to engage in moderate everyday transactions in order to sustain their livelihood, while only a very small minority can afford very high expenses. We argue that, if we find that moderate expenses represent the bulk of consumption in Bronze Age Europe, then we might be able to pinpoint the economic agency of the ‘invisible majority’ of average, non-elite individuals, and conclude that prehistoric consumer behaviour was not, in principle, fundamentally different from ours.

We explore the role of money in reconstructing consumption patterns, and test the consistency of the consumer model with the archaeological data through simulations. This study is based on a dataset of 23,711 copper and copper-alloy objects distributed in a vast sample area stretching through northern and southern Europe (Italy, Switzerland, Austria, Slovenia, and Germany) between c. 2,300-800 BCE (tab. 1; see Methods for a detailed breakdown). The sample has been divided into three broad phases (fig. 1): Phase 1 (c. 2,300-1,500 BCE; n=8,417), corresponding to the Early Bronze Age (EBA) and the first half of the Middle Bronze Age (MBA); Phase 2 (c. 1,500-1,100 BCE; n=7,759), corresponding to the second half of the MBA and the early phase of the Late Bronze Age (LBA); Phase 3 (c. 1,100-800 BCE; n=7,535), corresponding to the late phase of the LBA.

The problem we tackle first is the identification of a frame of reference to quantify consumption in prehistoric Europe, i.e., the value of all transactions in a given time period. We briefly illustrate the state of the debate around the identification of metallic money in the Bronze Age, and explore the evidence in support. We specifically address the connection between the spread of weighing technology in the course of the 2nd millennium BCE and the growing practice of metal fragmentation. We show that, starting c. 1,500 BCE, metal fragments represent the overwhelming majority of the sample of metal objects and systematically comply with weight systems. We argue that, since mass was a universal measure of value in the Bronze Age world, the evidence supports the interpretation of metal objects as money, intentionally broken down to match transaction values. The positive identification of weight-regulated money opens the way to address the observed mass values of metal objects as proxies of consumption in Bronze Age Europe.

We then find that mass values of metal fragments become log-normally distributed around 1,500 BCE, i.e., precisely when they start complying with weight systems. Our goal is to assess the likelihood that the log-normal distribution of metal fragments was determined under conditions similar to contemporary Western economies, i.e., that the distribution of household consumption is approximately equal to the distribution of income, with supply and demand at equilibrium. We test our hypothesis by simulating different scenarios and checking their consistency with the archaeological data. First, we test the null-hypothesis that random fragmentation can produce log-normal distributions by chance. We find that the outcome of random fragmentation is not consistent with the archaeological data after c. 1,500 BCE, and conclude that log-normality cannot arise by chance, requiring instead some form of constrained behaviour. We then simulate a monetary-exchange scenario, assuming that the available metal stock (=money) is random, but the prices of goods available for purchase (=supply) are log-normally distributed. We then observe the distribution of the metal that is given out in payment (=consumption) and show that, if supply is log-normal, the final distribution of consumption will likely be log-normal as well. We find that results are consistent with the archaeological data, and conclude that they support a model of log-normally distributed consumption for Bronze Age Europe starting c. 1,500 BCE, with copper alloys fulfilling the function of money.

RESULTS

Weight-regulated money: challenges and perspectives

The idea that bronze objects circulated as money in pre-literate Bronze Age Europe dates at least to the end of the 19th century [34]. Since then, research on this topic has largely focused on the relationship between metal objects and weight systems, remaining somewhat sporadic for the best part of the 20th century[35,36], until experiencing a renewed interest in the 1980s and 1990s[37–40]. Metrological research on metal objects has never produced significant impact on the mainstream discourse, likely as a consequence of two inherent limitations: on the one hand, the methodological framework is traditionally based on merely descriptive statistical techniques, on the other – and perhaps most importantly – it was never carried out in parallel with research on balance weights, until very recently.

These limitations are deeply interconnected. While there have been attempts at reconstructing the weight units of Bronze Age Europe starting from metal objects [37,41], research on balance weights only began on the verge of the 2000s[42–44], and the first systematic assessment of bronze age weight systems came roughly 20 years later[45]. It follows that, until very recently, there was no reliable comparative framework that could validate or disprove metrological reconstructions based on metal objects. Furthermore, it was actually research on balance weights that first introduced what today is considered the standard statistical technique in metrological studies[42,46], which in turn was applied to metal objects for the first time only a few years ago[14,47,48]. From a methodological point of view, the importance of an independent assessment of the metrological configuration of balance weights cannot be overstated. Simply put, weight-based regulation cannot happen without balance weights[12], and if weights were used in the process of weight-based regulation, then the weight-regulated material must have the same metrological configuration of balance weights.

A further limitation of previous research is that it tends to single out only those artefacts whose typological characters would seem to indicate an emphasis on formal standardization[12], such as ring- and bar-ingots in the Early Bronze Age[13,40,49], and sickles and axes in the Middle and Late Bronze Age[36,38,39]. While this can facilitate data collection, it may also lead to overlook overarching patterns. Moreover, it entails the risk of selection bias, that can in turn lead to circular argumentations.

Here, we analyse the complete sample of metal objects from Bronze Age hoards without typological distinctions, and compare its metrological properties to widespread weight systems independently reconstructed based on balance weights. Our rationale is that, if there is indeed a relationship between metals and weight systems, then this relationship must be detectable on large samples, regardless of the shape of the objects. The only meaningful distinction we make is between complete and fragmented objects, as they imply two completely different purposes of weight-based regulation. For complete objects to comply with weight systems, in fact, one must imply that the final mass was predetermined at the production stage, and hence it must have been imposed onto the final products by specialised metallurgists. On the contrary, weight-based fragmentation can have been enacted by any end-user – as it does not require any specific skill or equipment[50,51] – hence being entirely dictated by convenience and circumstances.

Fragmentation and money

The term 'hoard' designates an assemblage of metal objects buried simultaneously, in most cases with no clear spatial connection with settlements (fig. 2). For Bronze Age Europe, the vast majority of known metalwork comes from hoards, vastly outnumbering any other source of archaeological materials, such as settlements and burials. Hoards are one of the 'hot topics' in Bronze Age research, and are alternatively interpreted as votive depositions, metallurgists' stocks, and reserves of value [52]. Here, we do not focus on why hoards were buried, but only on how objects circulated before being buried. Based on previous research [14,53], we assume that, regardless of the reason behind their interment, hoards collect a statistically relevant sample of all the metalwork that was in circulation around the time of their deposition.

Research on the monetary circulation of metals in the Bronze Age of Western Eurasia mainly focusses on the intersection of metal fragmentation and weight-based regulation. Textual and archaeological evidence from Bronze Age Mesopotamia unequivocally shows that the invention of weighing technology c. 3,000 BCE produced a revolution in trade, establishing the concept of mass as the prime determinant of economic value, and prompting in time the widespread use of weight-regulated metal scraps as money [47,54–56].

Recent research suggests that the spread of weighing technology in Bronze Age Europe produced the same effects, indicating that bronze fragments fulfilled the same function of silver scraps in Mesopotamia [45]; here we illustrate a final assessment of the evidence based on our exhaustive database of European hoards.

Phase 1 hoards are composed almost exclusively of complete objects (92% on average; fig. 3), with many hoards containing large selections of a single object-type (e.g., daggers, axes, ingots), sometimes so regular in shape to suggest the possibility that they could come from the same mould[57–60]. The configuration of hoards changes dramatically in the course of the 2nd millennium BCE. Fragments tend to replace complete objects in European hoards in the course of the Bronze Age, rising from 8% on average in Phase 1 to 75-74% in Phase 2-3[61] (fig. 3). The rise of fragmentation appears to be strictly correlated with the diffusion of weighing technology (fig. 3). In Phase 1, weighing equipment is only sporadically attested in Italy[62], hence it cannot have been employed to regulate the complete objects that were deposited north of the Alps, where the largest share of our Phase 1 sample comes from. In Phase 2, however, the sudden spread of weighing technology between Northern Italy and Southern Germany is clearly correlated with the area of highest frequency of fragments. Finally, the appearance of balance weights in Northern Germany in Phase 3 corresponds to a visible rise in the share of fragments in that region.

Our analysis is specifically aimed at verifying the possibility that metal objects were produced and/or fragmented in order to comply with widely uniform weight systems that could rely on the widespread use of weighing technology. We rely on previous research identifying a 'Pan-European unit' of c. 10 g (with CV ≈5%), widely attested in Italy (starting c. 2,300-2,000 BCE), Central Europe (starting c. 1,500-1,350 BCE) and Atlantic Europe (starting c. 1,200-1,100 BCE)[45]. We use Cosine Quantogram Analysis (CQA) to test for weight-based regulation, and analyse complete objects, fragmented objects, and balance weights separately (Extended Data fig. 1-3). CQA is a standard technique in metrological studies of the Ancient World [46,63,64], aimed at verifying whether a significant share of metrical measurements in a sample is the product of a single 'quantum', i.e., a unit of measurement (see Methods).

Results show that, starting Phase 2, both balance weights and fragmented metal objects consistently comply with the 'Pan-European unit' of c. 10 g, while complete objects never show signs of weight-based regulation (fig. 4)[65]. A detailed analysis of the frequency distribution of the analysed samples supports the CQA results (Extended Data fig. 4-5, see Methods). The analysis of fragmentation patterns within individual hoards provides further insight on the purpose of fragmentation itself. Quantification shows that matching fragments within the same hoard are extremely rare, between 2-4% on average[61] (see Methods). This strongly suggests that objects were not broken immediately before being buried, rather supporting the hypothesis that fragments with different provenances circulated for a long time before being eventually buried [14,41,53].

In synthesis, results show that the fragmentation rate, the spread of weighing technology, and the systematic weight-based regulation of fragments are closely correlated on a continental scale, and support the hypothesis that metal fragments circulated as weight-regulated money starting c. 1,500 BCE.

Weight-regulated metal fragments as proxies of consumption

For the first time in history, the emergence of weight systems as a measure of economic value made it possible to convert the values of different quantities of different goods into one another, based on shared indexes of value[55,66]. Hence, being able to identify a substance that circulated as money – i.e., metal – provides us with the opportunity to indirectly measure the value of those transactions that involved weight-based monetary exchange. It provides, in other words, the opportunity to measure consumption.

We observed how metal fragments tend to comply with multiples of the Pan-European unit, meaning that they were broken down in order to match a predetermined transaction value. This, in turn, suggests that each single fragment was potentially used at least once as the means of payment in a transaction, and that the statistical distribution of their mass values is a proxy of the distribution of consumption. The Density Distribution Functions (DDF) and the Quantile-Quantile (Q-Q) plots suggest that the mass values of fragments become log-normally distributed starting Phase 2 (c. 1,500 BCE), while the fragments of Phase 1 and complete objects of all three phases show noticeable deviation from log-normality (fig. 5). The Kolmogorov-Smirnov test for normality supports the visual assessment (Extended Data fig. 6, see Methods). In particular, we find that the fragments of Phase 1 significantly depart from log-normality, the fragments of Phase 2 are log-normally distributed, and the fragments of Phase 3 do not depart from log-normality to such an extent that it invalidates modelling based on the assumption that they are log-normally distributed.

These observations suggest the possibility that, similarly to contemporary western economies, consumption in prehistoric Europe tends to follow a log-normal distribution at least as soon as metal fragments begin circulating as money. In contemporary western countries, households' income is unequally distributed and tends to follow a log-normal distribution, meaning that average incomes are, at the same time, vastly lower and more frequent than very high incomes, but only moderately higher and more frequent than very low ones[67,68]. Since households choose what to consume based on their income, it follows that consumption is also log-normally distributed[30–32], i.e., average expenses are vastly smaller and more frequent than very high expenses, but only moderately higher and more frequent than very low ones. In other words, since households will spend proportionately to what they earn or expect to earn, and since (expected) income follows a log-normal distribution, consumption does too.

In the next sections, we explore the circumstances under which we can expect the mass values of metal objects to eventually follow a log-normal distribution. Since we only know the outcome of the process (i.e., the mass values of metal fragments), we assume that the initial distribution of metal is always random, and we set out to determine the likelihood of different scenarios to produce log-normally distributed results out of randomly-distributed populations. We simulate two scenarios: One in which fragmentation is random and unrelated to consumption, and one in which it is functional to monetary exchange.

Simulation Scenario 1: Random fragmentation.

Traditional interpretations theorize that metal objects in Bronze Age Europe were broken down either for ritual purposes – e.g., to symbolically 'kill' the object, or to create 'bonds' between the owners of different fragments of the same object – or in order to facilitate remelting[18,21,52,69,70]. These models acknowledge neither weight-based regulation nor monetary circulation. Since both hypotheses imply that the main point of fragmentation was simply to destroy the object, they can be easily modelled as random fragmentation[53].

Here we test the null-hypothesis that a completely random fragmentation process can produce a log-normal distribution over time. We simulate a scenario in which a randomly-distributed stock of metal objects is randomly fragmented, and measure the outcomes[65]. Results show that the DDF of the simulated data is visibly left-skewed, and the Q-Q plots significantly diverge from log-normality (fig. 6). The archaeological sample of Phase 1 (which is not log-normally distributed) seems consistent with the random fragmentation model (fig. 6.A). However, the simulation is not consistent with the log-normal distribution of metal fragments of Phase 2-3 (fig. 6.B-C). A 2-sample Kolmogorov-Smirnov test coupled with bootstrap resampling confirms these observations (Extended Data tab. 1). In synthesis, results exclude that random fragmentation can produce log-normal distributions by chance, ruling out the ritual and recycling hypotheses for Phase 2-3.

Simulation Scenario 2: Monetary exchange

Since random fragmentation is not consistent with the archaeological data of Phase 2-3, we simulate an alternative scenario in which fragmentation is the result of monetary patterns of exchange. We designed this scenario in order to recreate the conditions according to which log-normally distributed consumption is expected to emerge in contemporary western economies. In Keynesian economics, production and expenditures tend to keep an economy stable by fluctuating according to the balance of supply and demand ('income-expenditure model')[71]. This is to say that an economy is expected to produce approximately as much as it can consume, and therefore aggregate income, consumption, demand and supply will theoretically tend to follow a similar distribution in the long run. It follows that, once the shape of the distribution of either of these variables is known, the remaining ones can be theoretically inferred.

For the purpose of this study, we assume that supply is log-normally distributed, and simulate fragmentation as the outcome of transactions at equilibrium prices, with the initial stock of metal having a random distribution. More in detail, we simulate a sell/purchase scenario in which an agent is assigned a random amount of metal stock and attempts to conclude transactions in a marketplace in which supply (=the prices of goods available for purchase) is log-normally distributed, with metal objects (=money) being fragmented to match transaction values[65].

Our expectation is that a randomly-distributed *initial* stock will produce a log-normally distributed *final* stock, in turn composed by log-normally distributed consumption (=the distribution of the individual values of all successful transactions) and a neglectable component of randomly-distributed 'unspent small change', regardless of the exponential growth of the number of fragments and with the final amount of metal in circulation remaining equal.

Our simulation consists of two input datasets (STOCK and SUPPLY) and one output dataset (CONSUMPTION). The routine simulates the exchange of metal objects for goods of equal value in a monetary fashion (fig. 7). STOCK simulates the randomly-distributed stock of complete metal objects available to a potential buyer at the beginning of a hypothetical cycle. We imagine STOCK as a finite quantity, gradually depleting after each iteration. We simulate SUPPLY as a virtually limitless, log-normally distributed array of prices of goods that are randomly resupplied at each iteration. In so doing, we intentionally emphasize the role of buyers, imagining them as a small group of people having potential access to every good in the marketplace, provided that they own enough money to pay for it. Pairs of potential buyers and sellers are randomly matched. When a potential buyer meets a potential seller, they attempt to conclude a transaction. If the value of the buyer's stock is approximately equal to the price set by the seller (i.e., ±5%, meant to account for the accuracy of Bronze Age balance scales[45]), the transaction takes place with the exchange of the full amount, and zero remainder (fig. 7.B). If the value of the buyer's stock is *significantly* higher than the price set by the seller (>105%), the buyer will break down the object, obtain a fragment whose value is equal to the value due in payment, and keep the remainder for themselves (fig. 7.C). If STOCK is *significantly* lower than SUPPLY (<95%), the transaction does not happen, and the entire value of STOCK is kept for the next transaction attempt (fig. 7.A). Each time a transaction is successful, its value is transferred to CONSUMPTION and removed from further iterations. Finally, if the transaction has a remainder, this is transferred to the next iteration of STOCK.

The simulated datasets are all log-normally distributed (Extended Data fig. 7). The simulated data for Phase 1 produce very high dispersion, as expected due to the small size of the archaeological sample (Extended Data fig. 7.A); despite this, the Q-Q plot shows higher divergence from the simulation than in the previous scenario. On the contrary, the simulations for Phase 2 and 3 produce very low dispersion, and are consistent with the archaeological datasets (Extended Data fig. 7.B-C). We take the outcome of the simulations as a fitting representation of the archaeological record of Phase 2-3, ultimately composed by fragments that actually played a role in at least one transaction during their 'lifetime'.

The simulation results show that, under the assumption that metal fragments circulated in a monetary fashion, their observed log-normal distribution can be explained by postulating an equally log-normally distributed supply, starting c. 1,500 BCE. In synthesis, results support the hypothesis that the observed distribution of consumption can be explained under the income-expenditure model.

DISCUSSION

To summarise, our results show that:

- Metal fragments of Phase 1 do not show signs of weight-based regulation, their mass values do not follow a log-normal distribution, and their distribution is consistent with random fragmentation;
- Metal fragments of Phase 2-3 comply with weight systems, are approximately log-normally distributed, are not consistent with random fragmentation, and are consistent with monetary-fragmentation;
- Complete objects never show signs of weight-based regulation.

We find evidence that, starting c. 1,500 BCE, consumption in prehistoric Europe tends to follow a log-normal distribution, similarly to contemporary Western economies. This suggests that, similarly to individuals in today's Western countries, prehistoric individuals made economic choices based on what they earned or expected to earn. Besides, log-normally distributed consumption also implies economic inequality[72]. Our results urge rethinking economic agency in prehistory, suggesting that inequality was not just a matter of prestige and status, but possibly affected the ability of individuals to fulfil their own needs and wants through selling and purchasing things, and perhaps services.

The log-normal model of consumption implies that petty, everyday transactions represented the majority of all transactions that took place within a period of time. This in turn suggests the existence of local markets for massively exported goods, whose demand was fulfilled at least in part through many small monetary transactions. This allows us to imagine a world in which individuals and households could integrate what they did not produce themselves through economic transactions, for example by purchasing common goods such as raw and processed food, textile fabric and clothes, tools, and novelty items.

The appearance of log-normally distributed consumption coincides with three correlated, continental-scale phenomena: 1) the spread of weighing technology; 2) the formation of a 'Pan-European' unit of mass; 3) the dramatic increase in the frequency of metal fragments and their circulation as weight-regulated money. Starting c. 1,500 BCE, metal becomes widely used as money, its value measured by weight. This was made possible by the introduction of weighing technology, which was not yet widespread in Europe before then. When metal becomes weight-regulated money, the distribution of its mass values becomes a reliable proxy of transaction prices.

Our findings neither imply that metal was the only form of money in prehistoric Europe, nor that money was the only mode of payment: credit, barter and redistribution all remain viable options contributing to the general picture. Rather, they suggest that monetary transactions paid in metal were frequent enough to provide us with a significant sample of the prices of all transactions that actually took place between c. 1,500-800 BCE. At the same time, we cannot exclude that money already existed before then. Recent research suggests that, centuries prior to the adoption of weighing technology, metallic money could rely on a rudimentary form of deviceless regulation based on 'sensory perception by hand and eyes', but so loose to be still compatible with the more generic notions of size and shape[13] (see Methods). The lack of device-based weight regulation is further supported by our tests, revealing no significant patterns in objects dating to the Early Bronze Age (fig. 4). However, even if weight was not the major determinant of value, it simply means that mass is not a reliable proxy of consumption, not necessarily that money did not exist.

While for earlier periods we find no evidence that metals are reliable proxies of consumption, we also find that the absence of weighing technology prevents monetary fragmentation, which in turn prevents the fulfilment of demand via the monetary circulation of metal *alone*. While this may cast doubts on the viability of metallic money before weighing, it does not rule out that different monies coexisted alongside one another. In the EBA, other substances (salt? Grains?) could also circulate as money, but we may not be able to identify them because they are not preserved. These substances may not even have required weighing technology, as they could be measured by volume. We know from Mesopotamian texts that capacity measures vastly predate the invention of weighing technology, that granular substances were measured by volume, and that some of them (e.g., barley) circulated as money [54,73]. Metals could already circulate as money in a limited fashion and concurrently with other substances, but their generalised monetary use was hampered by the absence of the necessary technology for the accurate quantification of their value.

By the same token, we cannot even exclude that consumption was already log-normally distributed before c. 1,500 BCE. The fact that, before then, metal is not a good proxy for consumption only means that we cannot take its statistical distribution as a reliable indicator, not necessarily implying that consumption was not itself log-normally distributed. By looking at the archaeological record, the shift to log-normality does not appear to have happened gradually but rather abruptly, as soon as weighing technology became widespread. This might suggest that the new technology did not generate a new behaviour, but rather facilitated the shift from a multitude of currencies that we are not yet able to detect towards a single main one – metal – other things remaining equal.

In this article, we addressed a sample region of Bronze Age Europe as a case study of economic behaviour in pre-modern economies. We found that general consumption patterns reveal widespread engagement of all strata of the population, granting archaeological visibility to a social category – the so-called 'commoners' – that is often overlooked by traditional models. Our results suggest that massive production and long-distance trade were not only driven by elite groups, but also by small-consumer demand in local markets. More generally, our results offer further empirical support to a growing body of research challenging elite-exclusive models of economic organisation of pre- and protohistoric societies in Western Eurasia: on the one hand, the wealth of written and archaeological evidence available for Bronze Age Mesopotamia shows the existence of a thriving private economy[73–76], on the other, local networks are more and more seen as foundational traits of international markets[45,77–79]. We conclude that the application of the concept of consumption to the quantitative analysis of prehistoric proxies of economic behaviour gives results that are consistent with the expectations for modern economies. At the same time, we do not find evidence that, as far as monetary exchange is concerned, the economic behaviour of prehistoric individuals was, in principle, fundamentally different from modern behaviour.

METHODS

The institutional setting of pre-literate Bronze Age Europe

The emphasis on elite agency and the political economy of pre-literate Bronze Age Europe (c. 2,300-800 BCE) mirrors a growing body of research on the macroeconomy of early state societies in the Mediterranean and the Near East throughout the third, second, and first millennia BCE, exploring the role of economic institutions in the formation of international markets[80–83].

West of Greece, however, pre-literate Bronze Age societies seem to have never developed state institutions. Although settlement patterns vary from region to region and from period to period, population was always organised in relatively small villages that never reached the size of the urban centres that developed elsewhere in Western Eurasia; they also never show unequivocal evidence of the embodiment of state institutions in public buildings, such as Near Eastern temples and palaces[84–86]. Compelling signs of state formation only appear at the beginning of the 1st millennium BCE – on the verge of the Iron Age – and tend to be concentrated in the Tyrrhenian basin, in those regions that would soon witness the rise of Etruscan city-states and, slightly later, of Rome[86,87].

While it is possible that the absence of writing may have hidden incipient forms of state-like institutions in the course of the 2nd millennium BCE, there is general consensus that the political landscape of Bronze Age Europe was splintered into a myriad of local chiefdom-like polities, whose governing elites could not extend their own authority much farther beyond regional boundaries[88,89]. This is to say that there was no single authority capable of providing the same kind of insurance that, say, the far-reaching political influence of the city of Aššur (Iraq) granted to commercial expeditions in Anatolia and Mesopotamia roughly in the same period[81]. There is also no clear evidence of informal institutions – such as associations of merchants – although recent studies are beginning to acknowledge the intense activity of professional traders in long-distance commercial networks[45,90].

At the same time, the absence of far-reaching authorities does not appear to have prevented the integration of pre-literate Bronze Age Europe in international markets[45]. The traditional model of a decentralised, but widely interconnected network of a multitude of local elites – bound by a complex system of alliances – offers then an alternative to state-formation to explain the evidence of long-distance trade and organised production[17,91,92]. This model, however, does not account for the agency of non-elite individuals in local markets – the so-called 'commoners'[17] – who may have produced a great deal of the available archaeological evidence, especially in an economic system in which institutions did not probably play an overwhelming role.

The sample area

The sampled area (Germany, Switzerland, Austria, Slovenia, Italy) represents a north-south cross-section of Europe, encompassing a wide diversity of geographical and cultural settings. Such a diversity is particularly apparent in the distribution of natural resources. Northern Germany is poor in metal ores, but the Baltic coast was a main source of amber, which was extracted and exported in large quantities across Europe and the Mediterranean, reaching as far as Mesopotamia[93–95]. The Erzgebirge region – a hypothetical source of tin – is located between Eastern Germany and the Czech Republic[96,97]. The Slovakian Ore Mountains – located just outside our sample area – were probably a major copper supplier during the Early Bronze Age, whereas mine districts located in the Eastern Alpine Arc seem to gradually take over in the later 2nd millennium BCE [6,98,99]. Finally, the most conspicuous natural resource of the Italian Peninsula – which could probably also rely on local copper ores[100] – was likely represented by its far-stretching coastline, that granted direct access to Mediterranean traffics[101].

Within a coarse grained, inclusive perspective such as the one we adopt in this study, this area can be considered as representative of a wider macro-territory, extending at least to its neighbouring regions. The sampled area, in particular, represents the geographical core of the phenomenon of metal fragmentation, which extended to the Danube Basin to the east[69,102], and to France and the British Isles to the west[52,53].

The sample of copper-alloy objects

The compilation of a database of European Bronze Age hoards has been carried out over the past 6 years as part of several research projects[14,61,103]. Data acquisition followed an inclusive strategy, aimed at the exhaustive collection of all the evidence ever published up to 2021, with a few additions after this date. Slovenia is the only exception, for which data collection is limited to the Late Bronze Age. While we cannot quantify potentially missing data, we are reasonably confident that the vast majority of contexts that are cited at least once in the scientific literature are accounted for. The full database is included in SI 1.

In total, 1,337 hoards were recorded, including 164 from Italy, 215 from Austria, 884 from Germany, 27 from Slovenia, and 47 from Switzerland. For each hoard, we recorded place of discovery (with geographical coordinates), relative chronology, and the deposited objects. For each object, we recorded general classification (e.g., axe, sword, collar, fibula, sickle, etc.), integrity/fragmentation, any potentially matching fragments, and mass.

The determination of whether an object is complete or fragmented was based either on drawings/photos or on the descriptions provided in the original publications. In cases where the conditions of the objects are not described and images are not provided, the information was not collected, and consequently, those objects were not used in our analyses. The mass values included in our database are those provided in the original publications of each context.

Out of a total of 30,989 catalogued objects, we excluded items from hoards without chronological information, as well as all objects made of gold, animal material, amber and stone, as they are not considered in the analyses. Among the remaining 30,487objects made of copper alloys, the complete/fragmented status of 23,711 objects could be determined. These include 8,417 objects from Phase 1 (complete = 6,968; fragmented = 1,449), 7,759 objects from Phase 2 (complete = 2,566; fragmented = 5,193), and 7,535 objects from Phase 3 (complete = 2,746; fragmented = 4,789) (tab. 1). For the purpose of log-transformations and Q-Q plots to establish the log-normality of the mass values of complete and fragmented objects, the objects made of copper alloys with published weights amount to a total of 13,627 (tab. 1), divided as follows: 4,955 from Phase 1 (complete = 4,558; fragmented = 397), 4,414 from Phase 2 (complete = 1,075; fragmented = 3,339), and 4,258 from Phase 3 (complete = 1,113; fragmented = 3,145).

Definition of chronological phases

In the sampled area, at least four chronological systems coexist: the Central European, Nordic, and Italian chronologies, in addition to the chronological horizons of the Late Bronze Age hoards from Slovenia. The sample includes contexts dating from the Early Bronze Age (c. 2,300 BCE) to the beginning of the 1st millennium BCE, except for Slovenia, for which sampling is limited to the Late Bronze Age (c. 1,350-800 BCE).

For the purposes of this study, we relied on the chronological attributions of the single hoards already established in the literature (fig. 1). An updated framework establishes a system of chronological horizons[60]. For Central Europe, the chronological phases originally present in the works of H. Müller-Karpe[104] and P. Reinecke[105] are still considered overall valid. For the approximate duration of each chronological phase, we rely on widely shared dates supported by radiocarbon dating (Brunner et al. 2020 for Bz A to C[106], Müller & Lohrke 2009 for Bz C and D[107], and Sperber 2017 for Bz D to Ha B3[108]). Our data collection stopped at the Ha B2 phase, c. 900 BCE.

For the Nordic chronology, we used the system of *Perioden* established by O. Montelius[109], which is still considered valid today. The absolute dates for the Late Neolithic and Period I phases were derived from Vandkilde et al. (1996)[110]. For the later phases, we relied on more recent radiometric dating[111]. Our data collection stopped at the Period IV, c. 900 BCE.

The chronology of Slovenian hoards is based on the sequence established in Turk (1996)[112] and includes only Late Bronze Age contexts. The first and second horizons correspond to Bz D and Ha A1 and A2 phases, respectively. The third horizon corresponds to Ha B1 and B2 phases. The subsequent horizon was not considered in this study.

For the Italian chronology, the division into periods is well-established (e.g., Carancini, Peroni 1999[113]). However, most of the available absolute dates pertain to the Early Bronze Age and the beginning of the Middle Bronze Age. Therefore, we mainly rely on cross-dating for the subsequent phases. For this study, we used the chronological framework presented in Cardarelli (2018)[114]. The lower limit of our data collection corresponds to hoards dated to the transition phase between Final Bronze Age 3 and Early Iron Age 1, c. 850 BCE.

In order to make it possible to compare developments across a wide region characterized by different local chronological schemes, we created three macro-phases (fig. 1), each containing approximately the same number of data (tab. 1).

The chronology of Bronze Age metallurgy in general, and of hoards in particular, almost entirely relies on typological seriation. As hoards are generally fortuitous finds with no clear connection to stratigraphies, direct absolute dating is generally impossible, and there is often no other way to date them than by relying on widely established typo-chronological schemes. Moreover, hoards often contain objects belonging to different chronological phases, or objects whose chronological attribution can be uncertain. Therefore, as a methodological rule, the date of a hoard is determined by its latest recognizable object. This does not mean that the chronology of hoards is uncertain: the typo-chronology of metalwork is solid and reliable, and connected to absolute dates thanks to the association of metal types with organic materials in settlements and burials. At the same time, the archaeological sequence is entirely conventional, and does not fully account for the nuances that can occur at the threshold between two contiguous phases. As a result, sometimes the attribution of single hoards can oscillate between two contiguous chronological phases.

This potential inaccuracy, however, is unlikely to affect our sample in any meaningful way. Part of the reason why we chose to group the sample into three broad phases is to limit the effect of potential chronological inaccuracy, by making sure that there would be no ambiguity for the majority of hoards falling in the middle of each phase. Inaccuracy, however, can still happen at the threshold between two phases, although its effects are likely negligible. The probability that the earliest hoards in, say, Phase 2 are in fact contemporary to the latest hoards in Phase 1 is the same probability of the latest hoards in Phase 1 being in fact contemporary to the earliest ones in Phase 2. This is to say that, while there is indeed an inevitable random error margin in the definition of archaeological phases, the symmetric distribution of this error on the boundaries between each phase eventually produces a zero sum, and it is unlikely to significantly affect the results of our analyses. Moreover, in such broadly defined phases, the error margin only affects those hoards that are in close proximity to the chronological boundaries, which are in turn a small minority.

Note on the sample of balance weights

The sample of weighing equipment considered in this study was collected and analysed in the last six years in the framework of a completed research project funded by the European Research Council[45]. The total sample includes 696 balance weights and 18 balance beams distributed unevenly across Europe, and covers a time span ranging approximately 2,300-700 BCE[62,64]. The sampling strategy was aimed at assessing the overall typological, chronological and metrological variability across Europe rather than at achieving significant quantification on local basis. As a result, some regional locales were relatively thoroughly sampled, while some others (such as Austria), were not sampled at all.

As illustrated in previous publications, European balance weights of the Bronze Age can be classified into two distinct orders of magnitude, corresponding to multiples and fractions of two different units of mass: a small unit of c. 10 g and a bigger unit of c. 400-450 g[14]. While the bigger unit – or *mina*, following the standard terminology of the Ancient Near East – is only attested in Italy and Central Europe, the smaller one – which one can call *shekel* – is attested virtually everywhere in Europe (hence dubbed 'Pan-European *shekel*). The subsamples for the *shekel*- and *mina*-ranges contain, respectively, 302 and 394 objects.

As illustrated in the next section, only the balance weights in the *shekel*-range were used in the statistical analyses. The full sample is included in SI 2.

Cosine Quantogram Analysis (CQA)

CQA[115] tests whether an observed measurement *x* is an integer multiple of a quantum *q* plus a small error component ε. *X* is divided for *q* and the remainder (ε) is tested. Positive results occur when ε is close to either 0 or *q*, i.e., when *x* is (close to) an integer multiple of *q*:

$$\phi(q) = \sqrt{2/N} \sum_{i=1}^{n} \cos(\frac{2\pi\varepsilon_i}{q})$$

where *N* is the sample size, and $\phi(q)$ is the test-statistic.

Bronze Age units of mass of between Mesopotamia and Europe have been extensively researched, with significant values ranging between c. 8.3 g ('Mesopotamian *shekel*'), and c. 10 g ('Pan-European *shekel*')[45].

The selection of the data to be analysed through CQA follows the guidelines described in Ialongo & Lago 2021[14]. The classification of balance weights into two orders of magnitude bears important implications for the metrological analysis of metal objects. As shown in Extended Data fig. 1, the distribution of the metal objects in our sample is approximately equal to or bigger than the distribution of weights in the *shekel*-range – with fragments largely overlapping – but overall smaller than the distribution of the *mina*-range.

Due to the limitations of the methodology employed, we cannot test fractions of a theoretical unit, but only its multiples. In other words, since most of the balance weights in the *mina*-range are heavier than most of the metal objects, we lack a statistically-significant sample to attempt a comparison. For this reason, our analyses are only aimed at testing the probability that the mass values of metal objects in European hoards are multiples of a *shekel* of c. 10 g.

Considering the particular configuration of the samples of metal objects and balance weights, the CQA was limited to a range comprised between 7-200 g, in order to avoid false positives and false negatives (Extended Data fig. 2). After sub-sampling, the analysis addresses c. 2/3 of the total sample of metal objects for which mass values are available (66% of fragments, 63% of complete objects). The blind-range of the sample of metal fragments does not represent a problem, as it almost entirely includes mass values below the lower limit of the analysis-range; below the *shekel* value, in fact, the accuracy of Bronze Age balance weights tends to drop exponentially, hence values significantly lower than the unit should be excluded anyway[64]. The blind-range of the sample of complete metal objects, on the other hand, can be partly made up for through Frequency Distribution Analysis, as illustrated below.

We analyse the chronological samples of balance weights, and complete and fragmented objects separately, and find that complete objects never show any sign of weight-based regulation, while fragments of Phase 2-3 give a high peak value at c. 10 g, corresponding to the 'Pan-European *shekel*' (Extended Data fig. 2). In order to enhance readability, the typical jagged lines produced by CQA were smoothed out with the 'smooth' function of the statistical package Wavemetrics IGOR Pro v. 6.0.5.0 (smoothing factor=1,000). We find that the balance weights do not show relevant values for the unit in Phase 1, but it must be considered that only a very small sample (n=18) is available for this phase. The unit of c. 10 g becomes relevant in Phase 2-3. In line with previous results[14], the results obtained from a much larger sample of metal fragments shows a similar pattern: The peaks for Phase 2-3 correspond to those obtained for balance weights, while fragments in Phase 1 do not show any relevant values. Finally, complete objects never show signs of weight-based regulation.

Quantograms of balance weights across Western Eurasia always produce roughly bell-shaped peaks around the unit value, reflecting the normally-distributed error margin of Bronze Age weight units with CV≈5%[45]. The quantogram of complete objects produces a random signal that is not consistent with the expectations for weight-regulated objects. On the other hand, the quantogram of bronze fragments produces a similarly bell-shaped peak around the value of the Pan-European unit, although with a wider dispersion. This is likely dependant on weight-regulated metal fragments having on average a wider error margin than balance weights, as a recent experimental study suggests, potentially reaching as high as CV≈30%[50]. Experimental research on the potential error margin of weight-regulated metal fragments, however, is only beginning and still based on small samples. It seems likely that the very wide error margin recorded by these experiments will shrink as sample size grows; at the same time, we should probably expect the inaccuracy of weight-based fragmentation to remain higher than that of balance weights, due to propagation of uncertainty.

Monte Carlo test for statistical significance

In metrological studies relying on CQA, it is standard practice to test the results' significance in order to exclude potential bias[62,63,116]. In our case study, the main potential source of bias is represented by the potential inaccuracy of the measurements collected in our database. The mass measurements we use in our analyses, in fact, were taken from a large and highly heterogeneous corpus of publications spanning over 150 years of research on Bronze Age hoards. We could not check the accuracy of every measurement; we can, however, frame the question as a problem of statistical significance.

We test the null-hypothesis that the recorded measurements are quantally-configured by chance. We assume that the measurements are only slightly off as a result of inaccurate instruments or transcription mistakes. We arbitrarily quantify potential inaccuracy as a random chance of each measurement of being within an interval of ± 15% from the recorded value, and run a Monte Carlo simulation. More in detail, we want to test the likelihood that a slightly different dataset can give better results than the recorded dataset. The rationale is that it is extremely unlikely that a dataset of thousands of measurements can give highly significant results by chance; therefore, if we find that the recorded dataset does not give the 'best possible results', then we should consider the possibility that the measurements are overall inaccurate.

We analyse the quantally-configured samples of metal fragments of Phase 2-3, run the Monte Carlo simulation for 1,000 iterations, each time recording the highest score for $\phi(q)$, and set an alpha level of .05. That is, if the randomised datasets give a value higher than the recorded datasets in more than 5% of the iterations, it means that the null-hypothesis is supported, and we cannot exclude that the peak value is due to chance.

The results of the Monte Carlo simulation are significant at alpha=.05, and reject the null-hypothesis (Extended Data fig. 3)[65]. We conclude that even if some level of measurement inaccuracy occurred in recording the data, it is unlikely to significantly affect the CQA results.

Frequency Distribution Analysis

Frequency Distribution Analysis (FDA) further clarifies the CQA results. Extended Data Fig. 4 shows the binned FDA of the bronze fragments for the three chronological samples, overlaid by the approximate distribution of the multiples of the Pan-European *shekel* of c. 10, visualised with CV=5% (1 SD). We limit the binned FDA to values up to c. 100 g, as beyond this value the sample only includes outliers (Extended Data fig. 1). Note that, for this range of values, the theoretical values of the multiples of the *shekel* never overlap at 1 SD. Despite being approximately log-normally distributed, the samples of Phase 2-3 are in fact roughly multimodal distributions of quantally-configured concentrations (i.e., their mean values are approximate multiples of the same quantum) with diffused background noise. The CQA detects these concentrations and indicates a best-fitting quantum corresponding to the Pan-European *shekel*, while the Monte Carlo simulation excludes that the background noise significantly affects the quantal configuration of the sample. The same analysis for the sample of metal fragments of Phase 1 does not show any relevant concentrations of values corresponding to multiples of the *shekel*, which is the reason why CQA cannot detect any relevant quantum.

The same analysis also clarifies why weight-based regulation likely did not occur for complete objects (Extended Data fig. 5). Complete objects show relevant concentrations of values in all chronological samples, but several arguments can be made that lead to exclude that these concentrations are the result of intentional weight regulation. The first argument is that the approximate mean values of these concentrations are never multiples of one another: Phase 1, for example, shows two peaks, a small one at c. 80 g and a much bigger one at c. 200 g, while Phase 2-3 have peaks at c. 100 and c. 170 g. If weight regulation really occurred in the production of these objects, their value concentrations should correspond to multiples of a unit-system, like in the case of fragments (Extended Data fig. 4) and balance weights in general [64].

The second argument is that these concentrations are too loose to have been determined by weight-based regulation. The concentration with mean c. 200 g visible in the FDA of Phase 1, for example, is so wide that the lightest objects (c. 120 g) are c. two times lighter than the heaviest ones in the same concentration (c. 240 g) the difference being so conspicuous that it is beyond doubt that their users could recognize it at a glance[13]. This is further supported by a comparison with the theoretical multiples of the *shekel* of c. 10 g. The overlaid values clearly show that these concentrations are so loose that they each encompass several possible multiples of the unit, and also that, at this magnitude, the error ranges of the multiples of the *shekel* systematically overlap. Overall, these observations strongly suggest that the Pan-European *shekel* cannot have been employed as a standard in the production of these objects, as it is also confirmed by the CQA results.

The third argument is the absence of any evidence related to the existence of weighing technology in Phase 1 North of the Alps, which is where most of the complete objects in our sample are located during this period.

These arguments are particularly relevant for evaluating the frequently proposed hypothesis that some formally-standardised objects dating to the Early Bronze Age (corresponding to our Phase 1) circulated as weight-regulated money [13,40,49]. Since the available evidence does not support weight-based regulation for complete objects in either chronological phase, there is no reason to think that the observed concentrations of mass values are correlated to anything else that the generic size and shape of the objects. In other words, complete objects were not regulated by the need to comply with weight systems, but rather by the need to conform to a certain generic size. In addition, the diachronic analysis clearly shows that loose concentrations of mass values are not unique to the Early Bronze Age, but they are a recurring feature of Bronze Age metalwork throughout the whole 2nd millennium BCE. In conclusion, since size (i.e., volume) and mass are obviously correlated, it makes little sense – in both analytical and interpretive perspectives – to separate these concepts when there is no evidence that one was more important than the other.

Goodness-of-fit tests

Research on contemporary western economies shows that sampling strategies slightly affect the shape of the distribution of consumption. While the distribution always tends to remain ‘approximately log-normal,’ different sampling strategies show results that are alternatively more or less consistent with strict log-normal models or with other distributions that look similar on charts, but that differ slightly in statistical properties, such as the Double-Pareto distribution[31,33]. This is reflected by log-normality tests, rejecting or validating the null-hypothesis depending on different sampling strategies. Testing for log-normality is further complicated by the very large size of the analysed samples, which dramatically lowers the requirements for H_0 to be rejected, and hence can produce false positives even when the effect size is extremely low[117–119]. However, despite its slight volatility, the distribution of consumption never seems to deviate from log-normality to such an extent that it invalidates general modelling based on the assumption of log-normality.

Our proxy-sample of monetary transactions in Bronze Age Europe is most likely affected by a similar sampling bias: it certainly documents only a part of all the theoretically-possible monetary transactions – which also probably involved media of exchange different from metal, that are not preserved – which in turn are only a part of the total amount of all theoretically possible transactions, which included transactions that were both monetary and non-monetary in nature. Furthermore, the large sample size of Phases 2 and 3 determines very low requirements for H_0 to be rejected. Therefore, similarly to research on contemporary consumption patterns, our question is not whether our sample is log-normally distributed, but rather whether the archaeological data deviate from a log-normal distribution to such an extent that it invalidates modelling based on the assumption of log-normality.

Following previous research on contemporary consumption patterns in Western Economies[31], we use the Kolmogorov-Smirnov test to assess the log-normality of our chronological samples, at α=0.05, while also assessing the test statistic (*D*) to evaluate effect size (Extended Data fig. 6).

The Kolmogorov–Smirnov test was performed on the log-transformed data using the `scipy.stats.kstest` function of the Python library `scipy`. The results for Phase 1 clearly reject H_0, with *p*=0.00001086 and *D*=0.123. The results for Phase 2, on the other hand, strongly suggest log-normality, with *p*=0.121 and *D*=0.020. Finally, the test rejects H_0 for Phase 3 (*p*=0.0002769), but the very low effect size (*D*=0.037) rather suggests that the difference between the sample distribution and the log-normal distribution is very small, which in turn suggests that assuming log-normality would not practically affect modelling in a significant way.

Simulations

To test the hypotheses described in scenarios 1 and 2, we conducted simulations using Python programming (Python Software Foundation. (2022). Python (version 3.9.12) [Software] https://www.python.org). All simulations were performed using an Ionic Series Laptop with the following technical specifications: CPU: 12th Gen Intel(R) Core(TM) i9-12900H 2.50 GHz. RAM: 16,0 GB. GPU: NVIDIA® GeForce® RTX 3070 Ti – RAM video 8,0 GB GDDR6.

Scenario 1 (random fragmentation)

Brief description

We generate an initial dataset of 1,000 values, and simulate fragmentation by generating 1,000 random fractional values, subtracting them from the initial dataset, and calculating the remainder, thus effectively doubling the initial dataset. This process is repeated 6 times; as fragmentation always produces two pieces, each time the number of objects is doubled, for a final dataset of 64,000 data points. For reference, we use the minimum and maximum mass values of the complete sample of metal objects included in our database (0.27-8,750 g) as boundaries for the generation of the initial random dataset. We repeat the entire process 100 times. In order to compare the results to the DDF of metal fragments, we randomly select 100 subsamples with the same number of data points of each chronological dataset (i.e., 397 for Phase 1, 3,339 for Phase 2, and 3,145 for Phase 3), standardize the data, visualize them in histograms, calculate the 95% Confidence Interval of each bin, and overlay the distribution of the corresponding chronological dataset.

Detailed description

For scenario 1, we created a `pandas DataFrame` with 1,000 numbers that follow a uniform distribution, with the minimum value equal to the mass of the lightest intact object (0.27 g) and the maximum value equal to the weight of the heaviest intact object (8,750 g) in our sample.

```
min_value = 0.27
max_value = 8750
complete_obj = pandas.DataFrame(numpy.random.uniform(low=min_value,
high=max_value, size=(1000,1)))
```

From the DataFrame "`complete_obj`" we simulated the random fragmentation of objects by dividing each element of "`complete_obj`" into two random parts and inserting the results into a list called "`fragm_list`". The same process is then repeated with all the elements of "`fragm_list`", each time doubling the number of elements. We performed the random fragmentation simulation six times, resulting in 64,000 fragments for each simulation. The results of each simulation are recorded in a column of the "`fragm_obj`" DataFrame. 100 simulations were conducted, resulting in 100 datasets, each containing 64,000 values.
The data obtained from the simulations were log-transformed using the code:

```
fragm_obj_log = numpy.log(fragm_obj)
```

and the columns were stacked into a single column of the DataFrame "`united_fragm_obj`".

```
united_fragm_obj = fragm_obj_log.stack().reset_index(drop=True).to_frame()
```

The data in "`united_fragm_obj`" were standardized:

```
mean_united_fragm_obj = united_fragm_obj.mean()
sd_united_fragm_obj = united_fragm_obj.std()
united_standardized_fragm_obj = (united_fragm_obj - mean_united_fragm_obj) /
sd_united_fragm_obj
```

At the same time, we imported the dataset containing the weight of the fragments for the three archaeological phases:

```
Arch_data = pd.read_excel('DB_SI.xlsx')
```

From which we filtered the weight of fragments and complete objects for each phase:

```
phase1_real = Arch_data.loc[(Arch_data['Phase'] == 1) &
                             (Arch_data['complete/fragmented/undetermined'] ==
                              'fragment') &
                             (Arch_data['Weight_obj'] > 0)].copy()
```

Then, we log-transformed and standardized the data for each phase in Pandas series. The archaeological data were plotted in subplots with histograms for each phase, showing the Kernel Density Estimation (KDE). Additionally, Quantile-Quantile Plots were included. In the same subplots, the distribution of the simulation data was also plotted, calculating the 95% CI based on 100 samplings, with each sampling consisting of a number of data points corresponding to the number of archaeological data available for each phase (397 for Phase 1; 3,355 for Phase 2; 3,154 for Phase 3). For the Quantile-Quantile Plots, the `statsmodels` library was used, while the histograms were created using the `seaborn` library. The time required to execute the entire script is 88.91 seconds.
The code for Scenario 1 is included in SI 3.

Scenario 2 (monetary fragmentation)

Brief description

The simulation consists of two input datasets (STOCK and SUPPLY) and one output dataset (CONSUMPTION). We simulate the fragmentation of 100 metal objects over a theoretical period of 100 iterations, and repeat the process for 100 runtimes.

We generate the data in the simulation by using the same parameters of the complete distribution of metal fragments included in our database as a reference. More in detail, we used the minimum and maximum mass values (0.27-8,750 g) as boundaries for the random generation of STOCK, and the average (3.207) and SD (1.72) of the log-transformed data to generate SUPPLY.

At the end of the 100 runtimes, we extract 100 random samples whose size is equal to the number of data points contained in each of the three chronological datasets (397 for Phase 1, 3,339 for Phase 2, and 3,145 for Phase 3). We then standardize the data, visualize them in histograms, calculate the 95% CI of each bin, and overlay the DDF of the corresponding chronological dataset.

Detailed description

For scenario 2, we created two `pandas` DataFrames, simulating a stock of initially intact objects to be fragmented from time to time for transactions. These transactions are not possible when the weight of the object (or fragment) to be exchanged is lower than the value of the item to be purchased. The dataframe '`stock`' is identical to '`complete_obj`', with a uniform distribution of values ranging from a minimum (0.27 g) to a maximum (8,750 g) based on the archaeological record, but with a size of 100 values.

The '`supply`' DataFrame has a log-normal distribution of data, with the mean and standard deviation based on the archaeological data:

```
mu = 3.207
sigma = 1.72
supply = pandas.DataFrame(numpy.random.lognormal(mu, sigma, size=(100, 1)))
```

With the elements of '`stock`', we simulate an attempt at an economic transaction by trying to purchase the elements from '`supply`'. The transaction is possible only when the value of '`stock`' is greater than or equal to (with a tolerance range of 5%, meant to take into account the accuracy of Bronze Age balance weights[45]) the value of '`supply`'. When it is lower, the transaction does not occur. If the element from '`stock`' used in the transaction is larger than that of '`supply`', and not within the 5% range, fragmentation of the object occurs. The weight of the element in '`stock`' is updated by subtracting the mass of the fragmented portion to execute the exchange. The value of all transactions – i.e., the weight of all fragmented pieces or intact objects involved in acquiring a commodity from the '`supply`' DataFrame - is recorded in the '`consumption`' DataFrame. The attempt at transactions is carried out 100 times, with the 'stock' DataFrame updating after each completed transaction, and the 'supply' DataFrame being regenerated in each cycle. We performed 100 simulations following the described procedure.
At the end of the simulations, the data from '`consumption`' and the remaining '`stock`' were merged into a single DataFrame called `'final_stock_consumption`'. Similarly to what was done in the simulations of scenario 1, the simulation data were log-transformed and standardized. We sampled 100 lists of randomly selected numbers from the DataFrame '`final_stock_consumption`', with the number of elements corresponding to the number of archaeological data available for each phase (397 for Phase 1; 3,355 for Phase 2; 3,154 for Phase 3). From these 100 samples, we calculated the mean and 95% CI, which were plotted alongside the KDE of the archaeological data and in a Quantile-Quantile plot with the

archaeological data. The archaeological data were imported using the same procedure described in Scenario 1. The time required to execute the entire script is 728 seconds.
The code for Scenario 2 is included in SI 4.

Simulation-scenario 1: Assessing goodness-of-fit

We have prepared the results of the simulation for the two-sample Kolmogorov-Smirnov test. Given that the DataFrame combining the results of all iterations performed in the simulation consists of about 6 million and 400 thousand data points, it was necessary to perform sampling of the same size as the archaeological fragments phase by phase (i.e., Phase 1=397, Phase 2=3,339, Phase 3=3,145).

```
sample_united_fragm_obj_ph1 = numpy.random.choice(united_fragm_obj_std_flat,
db_size_ph1, replace=False)
```

This operation was iterated in a loop for 1,000 times, calculating each time the p-value and the statistic (D) of the data sampled from the simulation against the archaeological fragments. The test was performed using the `scipy.stats.ks_2samp` function from the Python scipy library.

At each iteration, we collect the p-value and statistic (D) within a DataFrame and report the share of cycles in which the KS test gives $p>0.05$ (Extended Data tab. 1). At the end of the loop, we performed a bootstrap sampling of the means of the p-values and statistics and calculated the mean and statistic (D) with their Standard Deviations. The KS test results for Scenario 1 show that the simulation fits the data for Phase 1, but reject H_0 for Phases 2 and 3 (Extended Data tab. 1). We conclude that the KS test supports the visual assessment of the simulation outcomes, confirming that random fragmentation is consistent with the archaeological data for Phase 1 but not with those of Phase 2-3.

Data Availability

The authors declare that all data supporting the findings of this study are available within the paper and its supplementary information files.

Code Availability

Custom code that supports the findings of this study is available within the paper and its supplementary information files, and publicly available on Zenodo (https://zenodo.org/doi/10.5281/zenodo.10959515), under license CC BY-NC 4.0.

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Author Contributions

NI designed the research, performed data analysis, and wrote the article. GL performed data analysis, wrote the article, and created the code.

Competing Interests

The authors declare no competing interests.

fragments vs complete							
		Italy	Austria	Germany	Slovenia	Switzerland	total
Phase 1	complete	575	1,313	4,886	0	194	6,968
	fragments	78	162	1,190	0	19	1,449
	undetermined	574	601	2,942		17	
Phase 2	complete	159	247	1,828	144	188	2,566
	fragments	667	1,545	2,155	668	158	5,193
	undetermined	312	95	779	16	85	1,287
Phase 3	complete	666	448	1,463	137	32	2,746
	fragments	2,456	1,275	812	232	14	4,789
	undetermined	532	217	560	40	6	1,355
objects with known mass							
		Italy	Austria	Germany	Slovenia	Switzerland	total
Phase 1	complete	350	1,204	2,887	0	117	4,558
	fragments	61	47	287	0	2	397
Phase 2	complete	30	131	762	129	23	1,075
	fragments	450	1,175	993	636	85	3,339
Phase 3	complete	239	262	456	135	21	1,113
	fragments	1,706	893	301	232	13	3,145

Table 1. Breakdown of the sample of copper alloy objects.

Captions

Figure 1. Chronological framework. Correlation of regional chronologies and illustration of the chronological Phases used in this study.

Figure 2. The scrap hoard of Weißig (Germany). One of the largest hoards of the Late Bronze Age in Northern Germany (c. 20 kg) the hoard is composed by 63 complete objects and 328 fragments (courtesy of Landesamt für Archäologie Sachsen. Photo by J. Lipták).

Figure 3. Spatial analysis. Diachronic development of metal fragmentation in hoards and spread of weighing equipment. The gradient represents the Kernel Density Estimation of the ratio of fragments in hoards. Areas shifting to red have high frequency of hoards containing only (or almost only) fragments; blue-shifts represent areas with high frequency of hoards containing only (or almost only) complete objects. Pie charts show the total share of metal fragments in each chronological phase. Squares represent sites with weighing equipment, mostly settlements and burials; a single site can contain more than one balance weight. White squares represent balance weights actually documented in each chronological phase, while gray squares indicate presence in the previous phase. When a white square is present in the same spot in two consecutive phases, it means that a multi-stratified settlement has evidence of balance weights in both phases.

Figure 4. Quantal analysis. Cosine Quantogram Analysis (CQA) of metal fragments, complete objects, and balance weights, by chronological phase. Phi(q) is the test statistic (see Methods). Peaks indicate the value of the best-fitting quantum (i.e., underlying unit).

Figure 5. Density Distribution Function, Kernel Density Estimation, and Quantile-Quantile plots of the logarithmic distribution of mass values of metal fragments and complete objects, by chronological phase.

Figure 6. Simulation scenario 1: Random fragmentation. Green area: CI=95% of the simulated results (DDF and Q-Q plots). Green line: mean values of the simulated results (DDF and Q-Q plots). Orange lines: KDE of the distribution of metal fragments. Orange dots: Q-Q plots of the distribution of metal fragments.

Figure 7. Graphical model of simulation scenario 2: Monetary fragmentation. The model illustrates how the output dataset 'CONSUMPTION' is created, through the interaction between the input datasets 'SUPPLY' and 'STOCK'. When a hypothetical seller meets a hypothetical buyer, a single element is randomly extracted from SUPPLY, representing the hypothetical price of a single good on the marketplace. The price-element is then paired with another element randomly drawn from STOCK, representing a single metal object in the possession of a potential buyer, who is planning to use that same object as money. T this point, the simulation runs a test to verify one out of three possible scenarios: A) The money-object is less valuable than the price-element. In this scenario, the transaction does not happen and the money-object returns to STOCK, unspent; B) The money-object is as valuable as the price-element. The transaction takes place with no remainder, and the transaction value is transferred to CONSUMPTION. C) The money-object is more valuable than the price-element. The transaction takes place, and the money-object is broken down to obtain a fragment whose value is equal to that of the price-element. The transaction value is then transferred to CONSUMPTION, while the remainder (i.e., the 'leftover' fragment that was not used in the transaction) returns to STOCK, unspent.

Table 1. Breakdown of the sample of copper alloy objects.

EXTENDED DATA CAPTIONS

Extended Data Figure 1. Simulation scenario 2: Monetary fragmentation. Green area: CI=95% of the simulated results (DDF and Q-Q plots). Green line: mean values of the simulated results (DDF and Q-Q plots). Orange lines: KDE of the distribution of metal fragments. Orange dots: Q-Q plots of the distribution of metal fragments.

Extended Data Figure 2. Orders of magnitude. The boxplots show the distribution of the mass values balance weights pertaining to the *shekel*- and the *mina*-range, compared to the distribution of metal fragments and complete objects. Dotted lines indicate the approximate value of the weight units. Solid lines indicate the boundaries of the CQA sampling (7-200 g). *Shekel*: n=244, min.=0.16 g, max.=469.41 g, centre=9,.77 g, box bottom=4.08 g, box top=32.01 g, whisker bottom=0.16 g, whisker top=100.00 g. Fragments: n=6,881, min.=0.01 g, max.=9,220 g, centre=26.00 g, box bottom=7.90 g, box top=82.00 g, whisker bottom=2.70 g, whisker top=233.00 g. Complete: n=6,746, min.=0.27 g, max.=8,750 g, centre=181.00 g, box bottom=375.27 g, box top=210.00 g, whisker bottom=31.30 g, whisker top=340.00 g. *Mina*: n=367, min.=11.8 g, max.=5,050 g, centre=592.00 g, box bottom=375.27 g, box top=908.30 g, whisker bottom=235.20 g, whisker top=998.36 g. Outliers method: 1.5*Interquartile range. Graph made with Wavemetrics Igor Pro 6.0.5.0.

Extended Data Figure 3. CQA, diachronic results. Dotted lines represent the raw output of the quantal analysis. Solid lines represent the same output after smoothing. We indicate the number of measurements sub-sampled in each quantogram, and in parentheses the total sample size.

Extended Data Figure 4. Monte Carlo simulation. CQA of the sample of bronze fragments of Phases 2-3 compared to the CQA results for balance weights. Left Y axis: balance weights. Right Y axis: bronze fragments. The horizontal dashed line represents the 5% significance level for the Monte Carlo simulation (ϕ(q)=7.35), lower than the peak value of bronze fragments (ϕ(q)=7.77).

Extended Data Figure 5. Binned Frequency Distribution Analysis of metal fragments. Bin size=1.11 g. The dots overlaid on the histograms represent multiples of 10 g (i.e., the approximate value of the Pan-European *shekel*); the boundaries represent a CV=5% at 1 SD. The dots' Y values are arbitrarily placed for visual clarity. Above: Phase 1 (n=397). Below: Phase 2 (n=3,339) and 3 (n=3,145).

Extended Data Figure 6. Binned Frequency Distribution Analysis of complete metal objects. Bin size=11.1 g. The dots overlaid on the histograms represent multiples of the theoretical value of Pan-European *shekel* of 10 g; the whiskers represent CV=5% of each of these multiples at 1 SD. The dots' Y values are arbitrarily offset, in order to avoid visual confusion generated by the overlapping error margins. Above: Phase 1 (n=4,558). Below: Phase 2 (n=1,075) and 3 (n=1,113).

Extended Data Figure 7. One-sample Kolmogorov Smirnov test for normality (two-sided). The graphs compare the Cumulative Distribution Functions (CDF) of archaeological datasets and normal distributions. The *p*-values and test statistic *D* of each test are shown on the graphs.

Extended Data Table 1. Results of the bootstrapped two-sample Kolmogorov-Smirnov test (two-sided). The test compares the distribution of mass values of each chronological phase with a bootstrapped sampling of the simulation results for Scenario 1 – random fragmentation.

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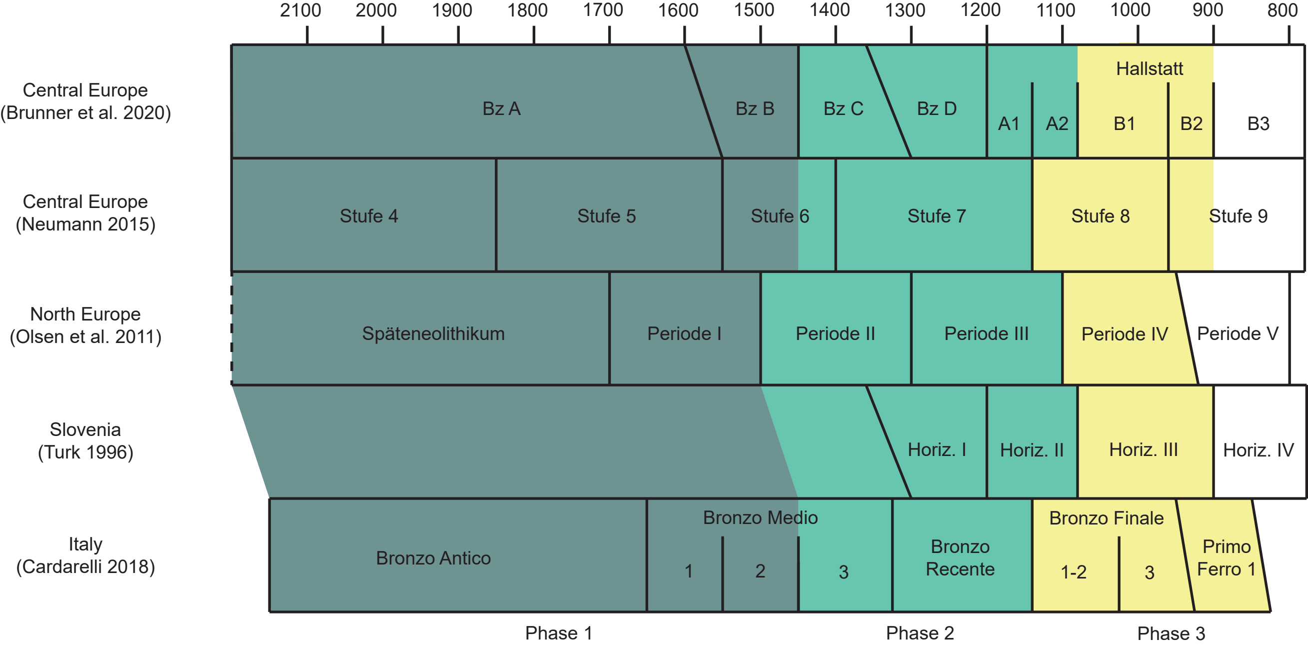
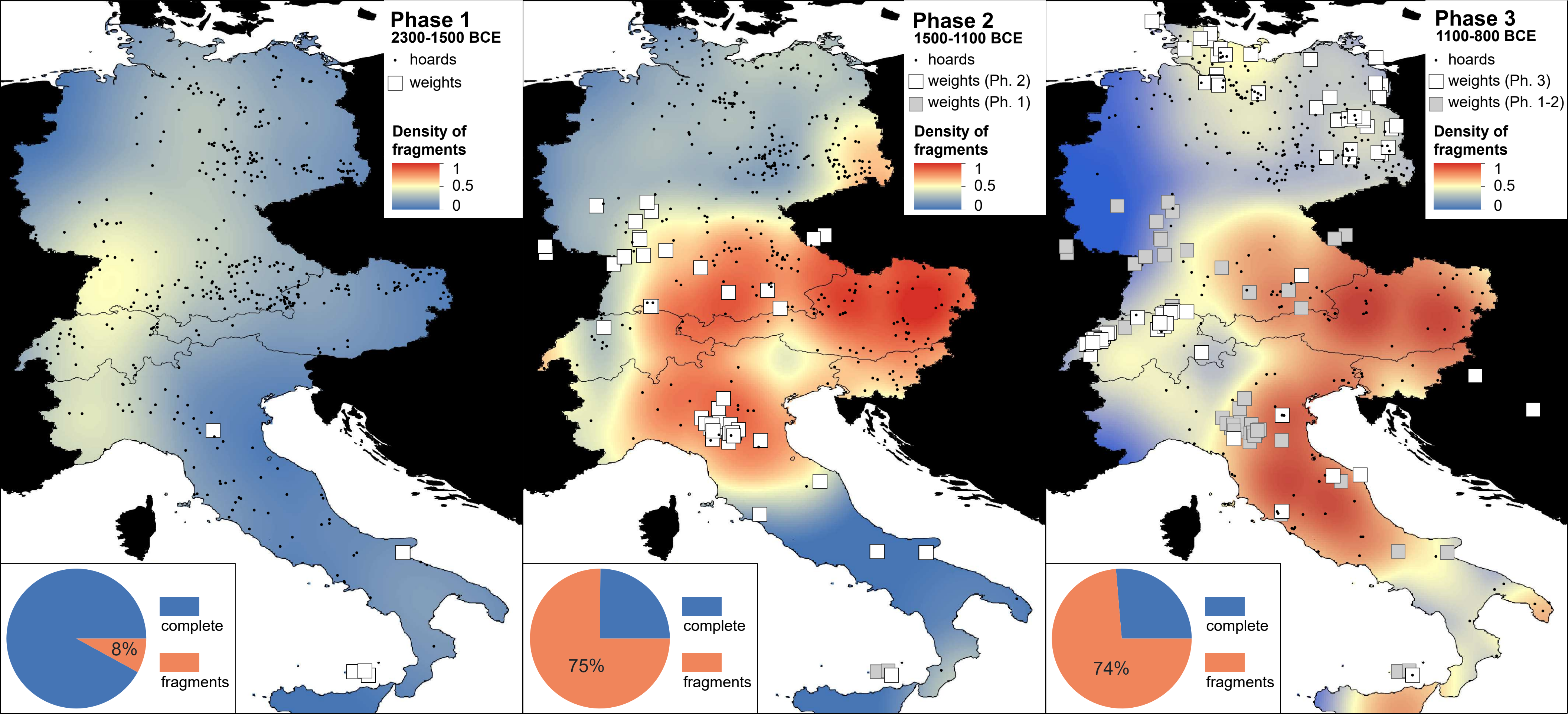
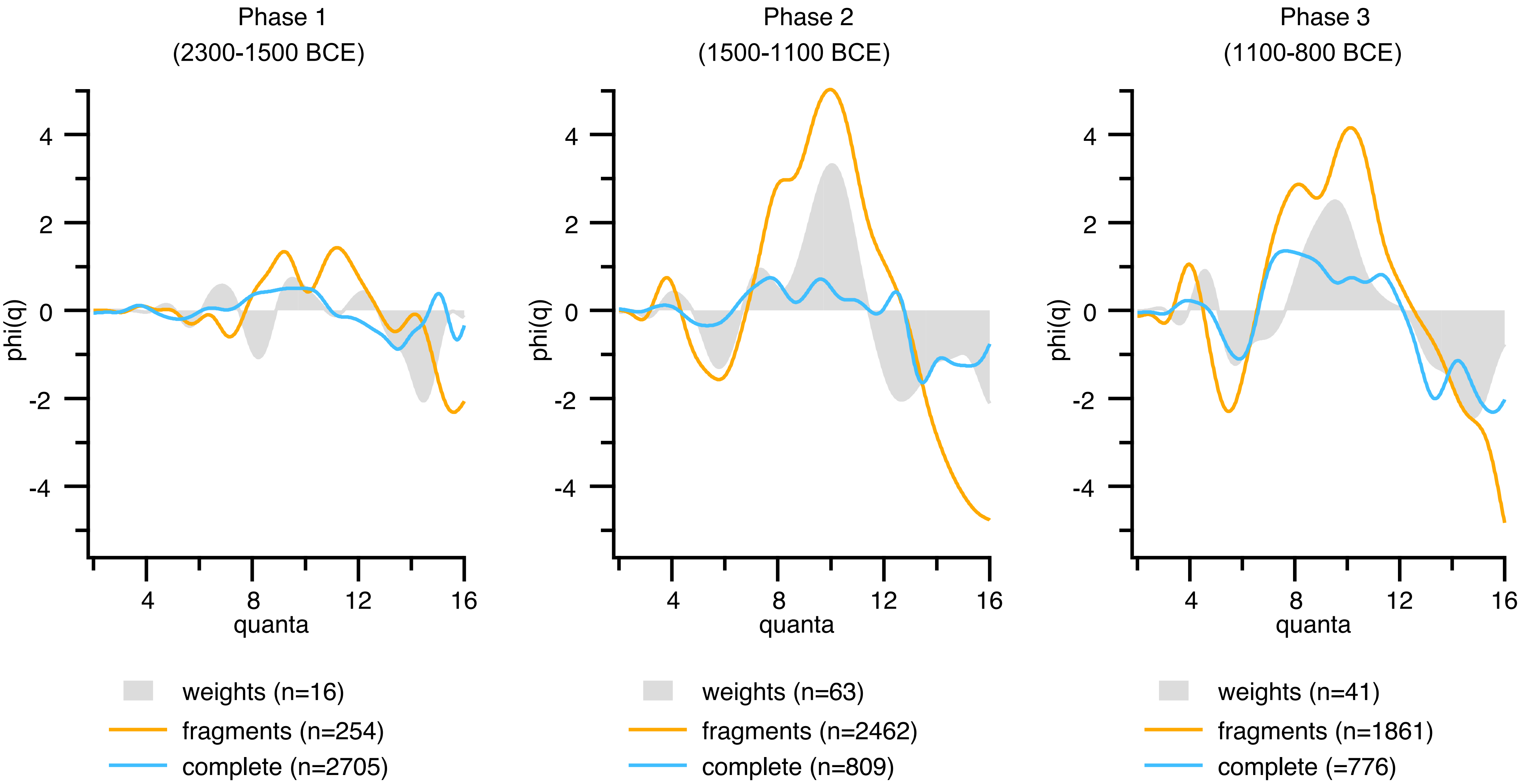
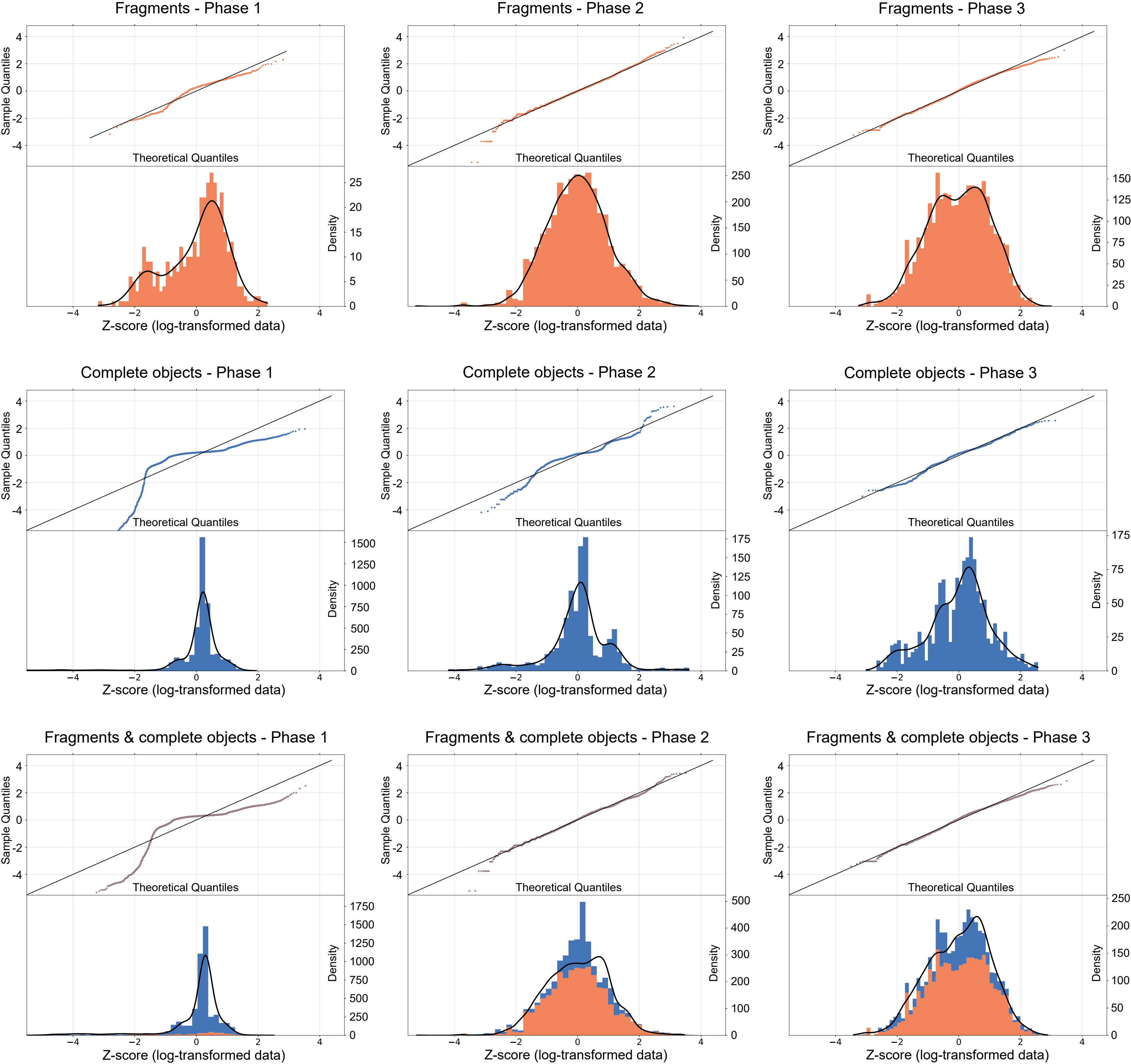
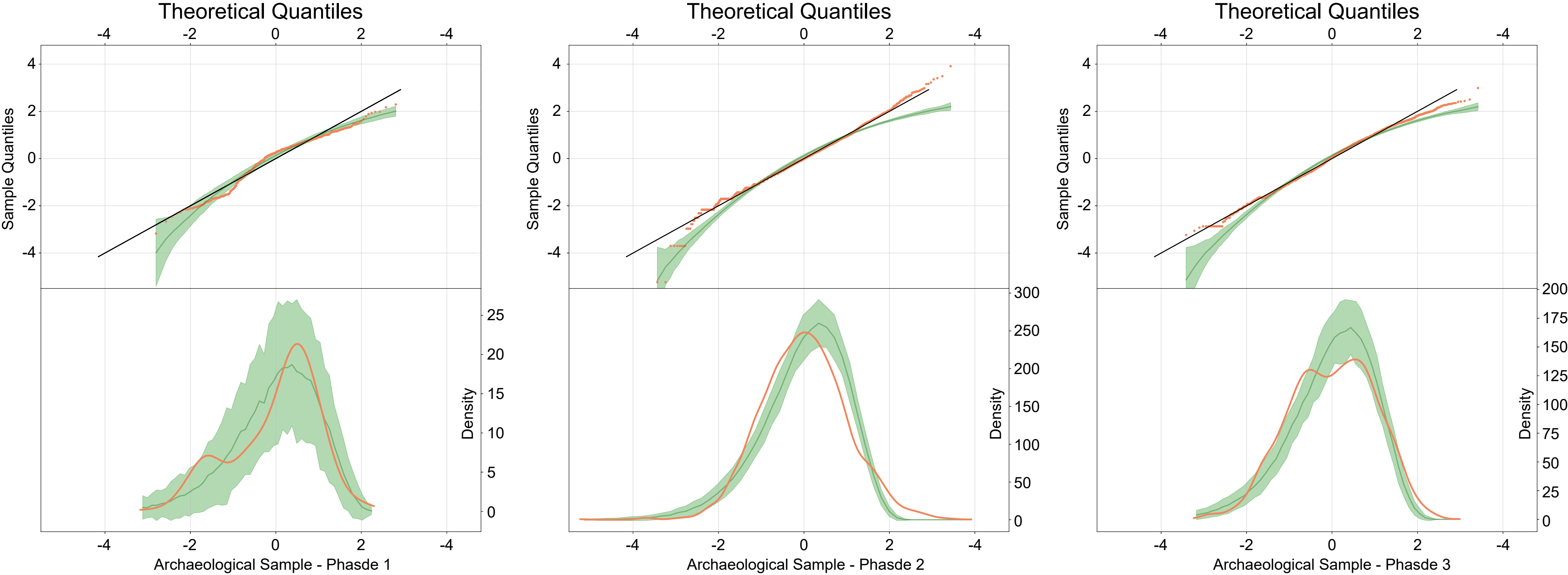

2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
Central Europe
(Brunner et al. 2020)
Bz A
Bz B
Bz C
Bz D
Hallstatt
A1
A2
B1
B2
B3
Central Europe
(Neumann 2015)
Stufe 4
Stufe 5
Stufe 6
Stufe 7
Stufe 8
Stufe 9
North Europe
(Olsen et al. 2011)
Späteneolithikum
Periode I
Periode II
Periode III
Periode IV
Periode V
Slovenia
(Turk 1996)
Horiz. I
Horiz. II
Horiz. III
Horiz. IV
Italy
(Cardarelli 2018)
Bronzo Antico
Bronzo Medio
1
2
3
Bronzo Recente
Bronzo Finale
1-2
3
Primo Ferro 1
Phase 1
Phase 2
Phase 3



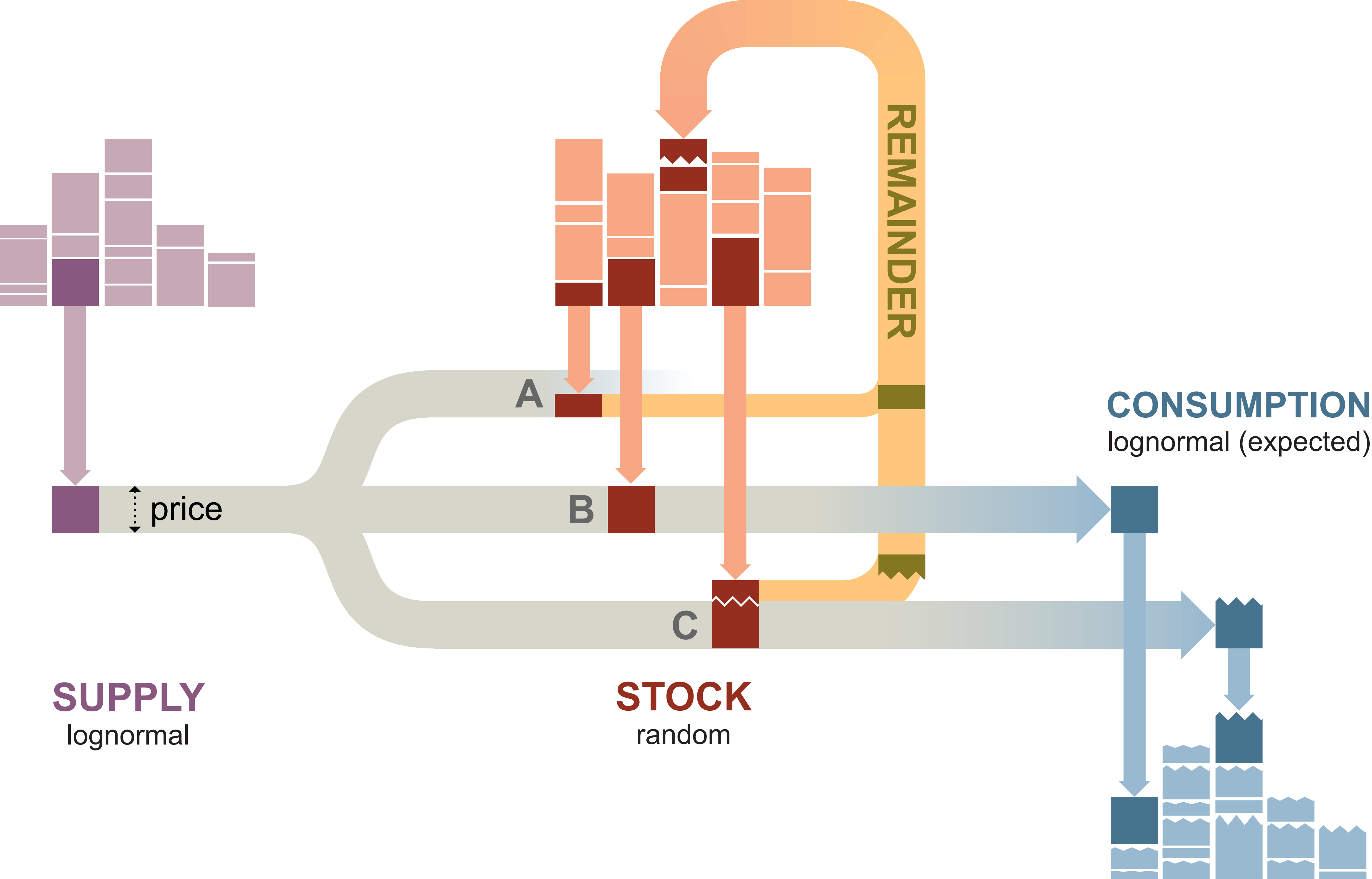
Phase 1
2300-1500 BCE
hoards
weights
Density of fragments
1
0.5
0
complete
fragments
8%
Phase 2
1500-1100 BCE
hoards
weights (Ph. 2)
weights (Ph. 1)
Density of fragments
1
0.5
0
complete
fragments
75%
Phase 3
1100-800 BCE
hoards
weights (Ph. 3)
weights (Ph. 1-2)
Density of fragments
1
0.5
0
complete
fragments
74%

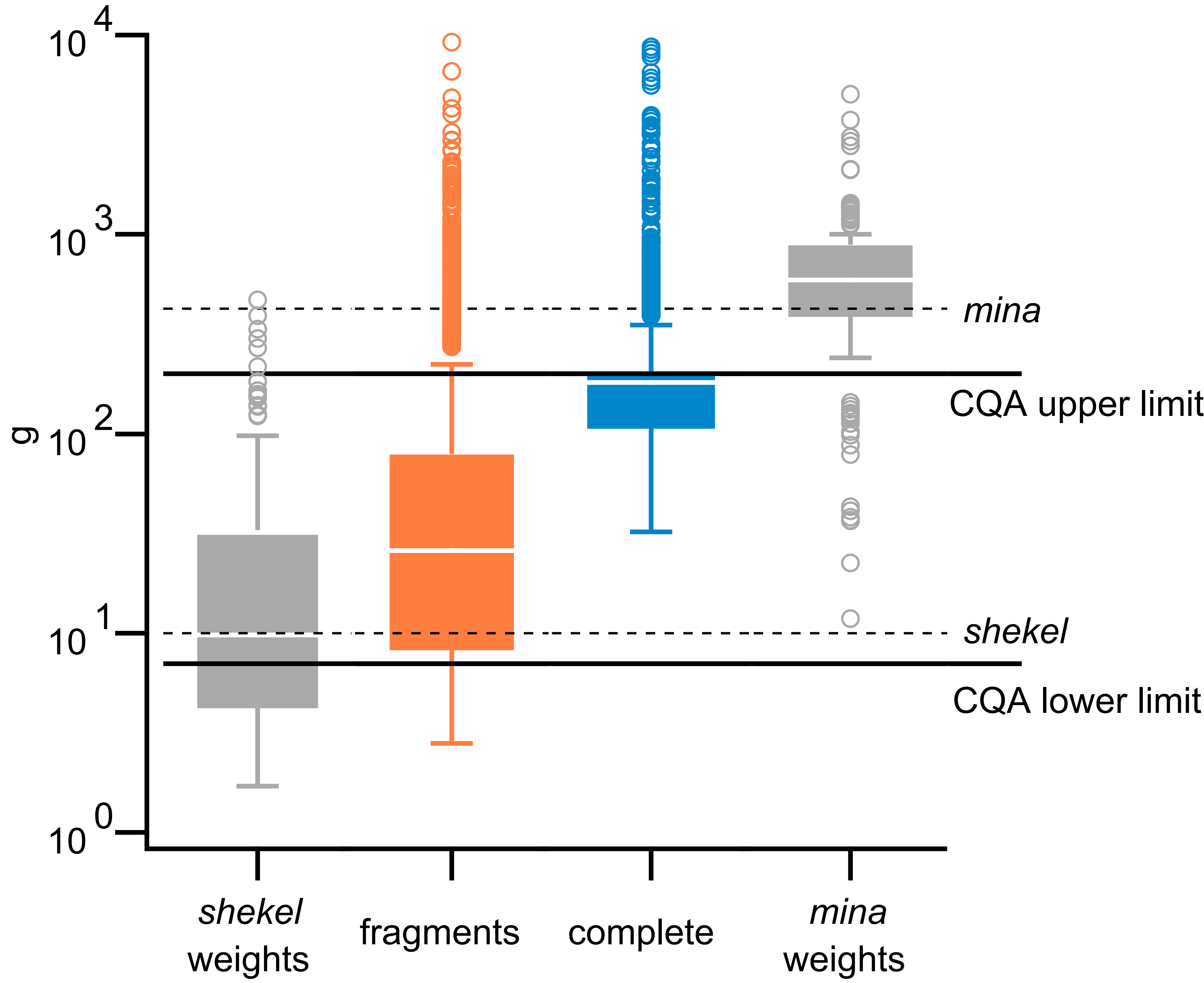

Phase 1
(2300-1500 BCE)
Phase 2
(1500-1100 BCE)
Phase 3
(1100-800 BCE)
phi(q)
quanta
4
2
0
-2
-4
4
8
12
16
weights (n=16)
fragments (n=254)
complete (n=2705)
weights (n=63)
fragments (n=2462)
complete (n=809)
weights (n=41)
fragments (n=1861)
complete (=776)

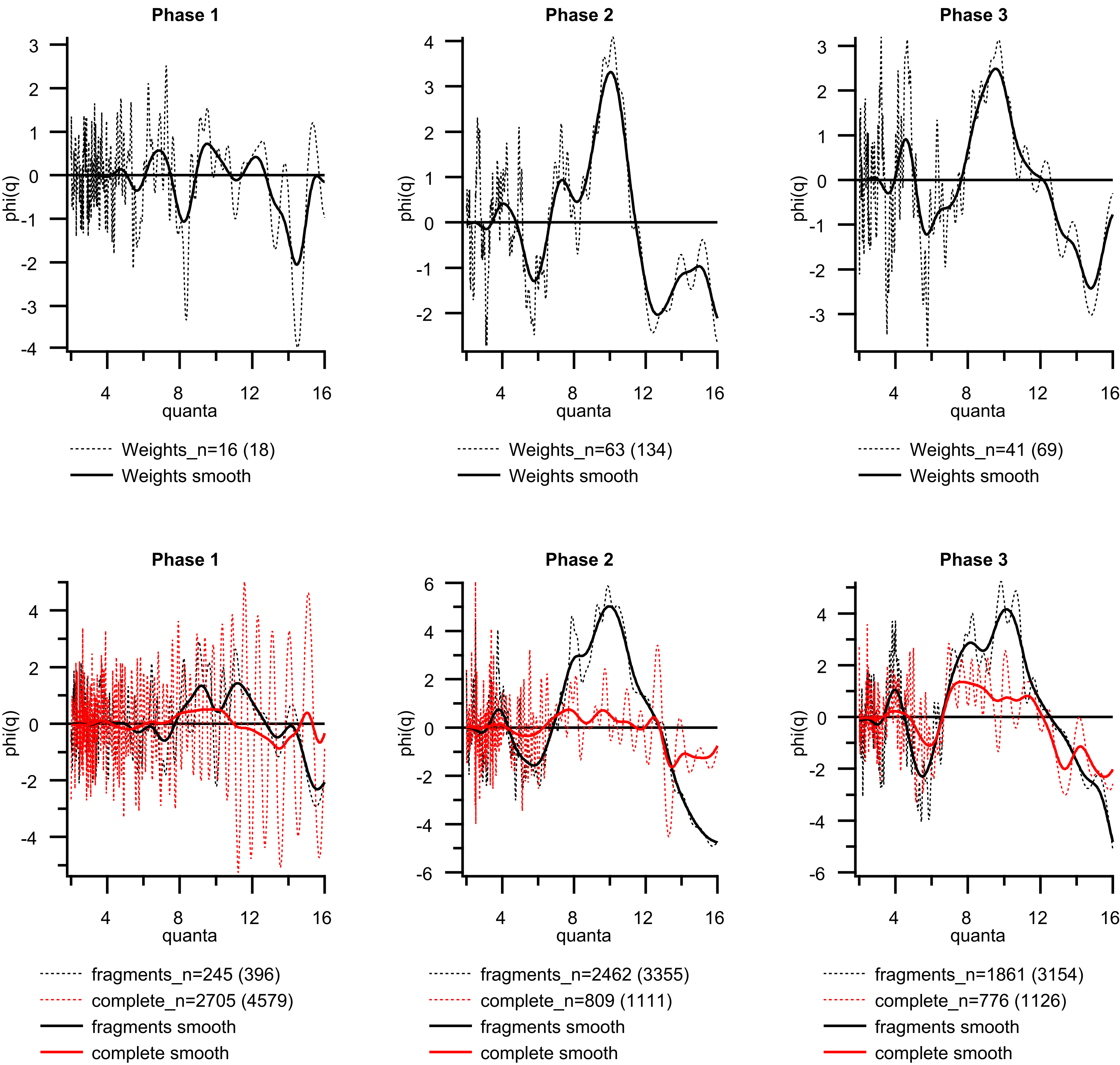

Fragments - Phase 1
Fragments - Phase 2
Fragments - Phase 3
Complete objects - Phase 1
Complete objects - Phase 2
Complete objects - Phase 3
Fragments & complete objects - Phase 1
Fragments & complete objects - Phase 2
Fragments & complete objects - Phase 3
Sample Quantiles
Theoretical Quantiles
Density
Z-score (log-transformed data)

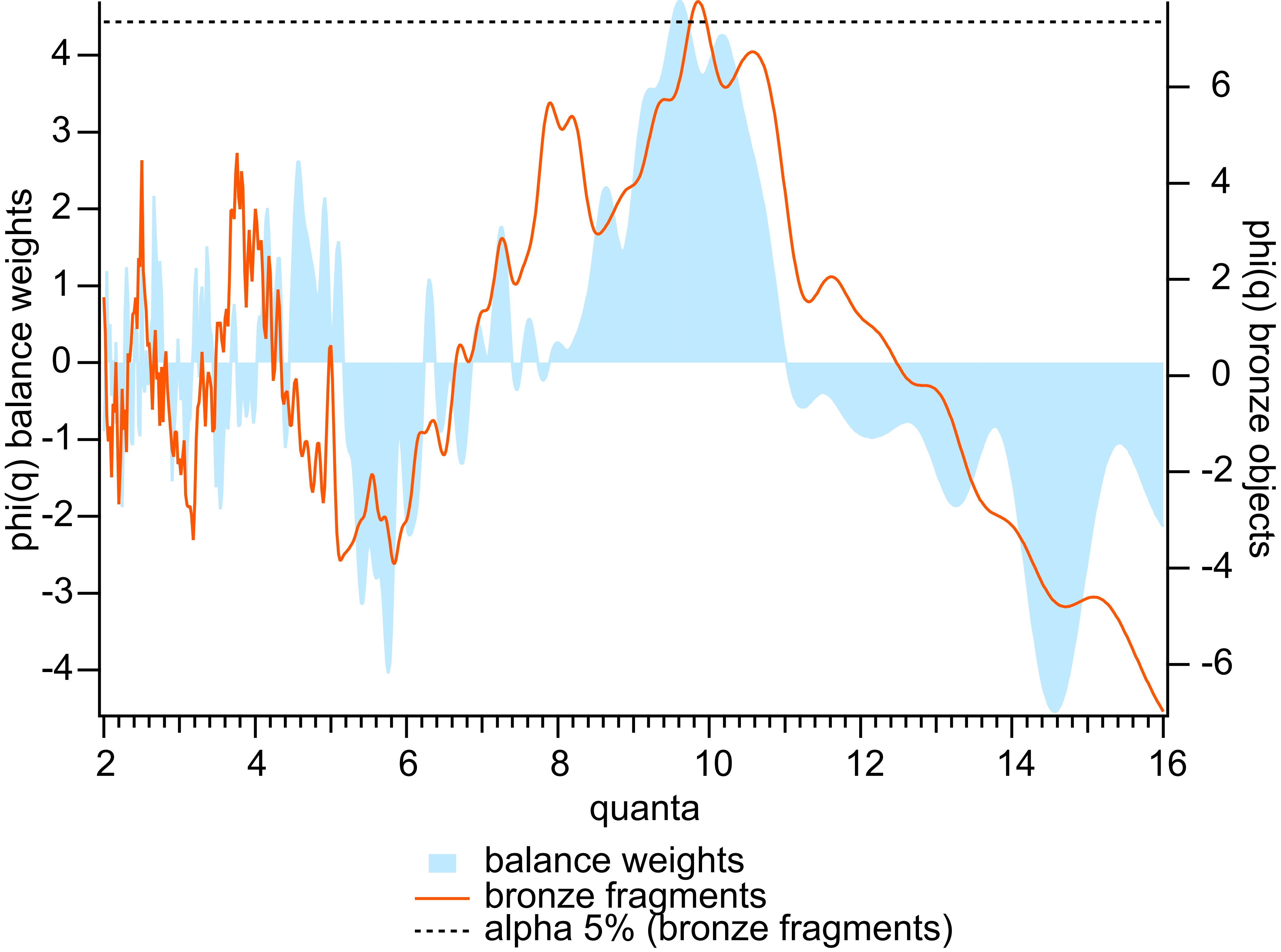


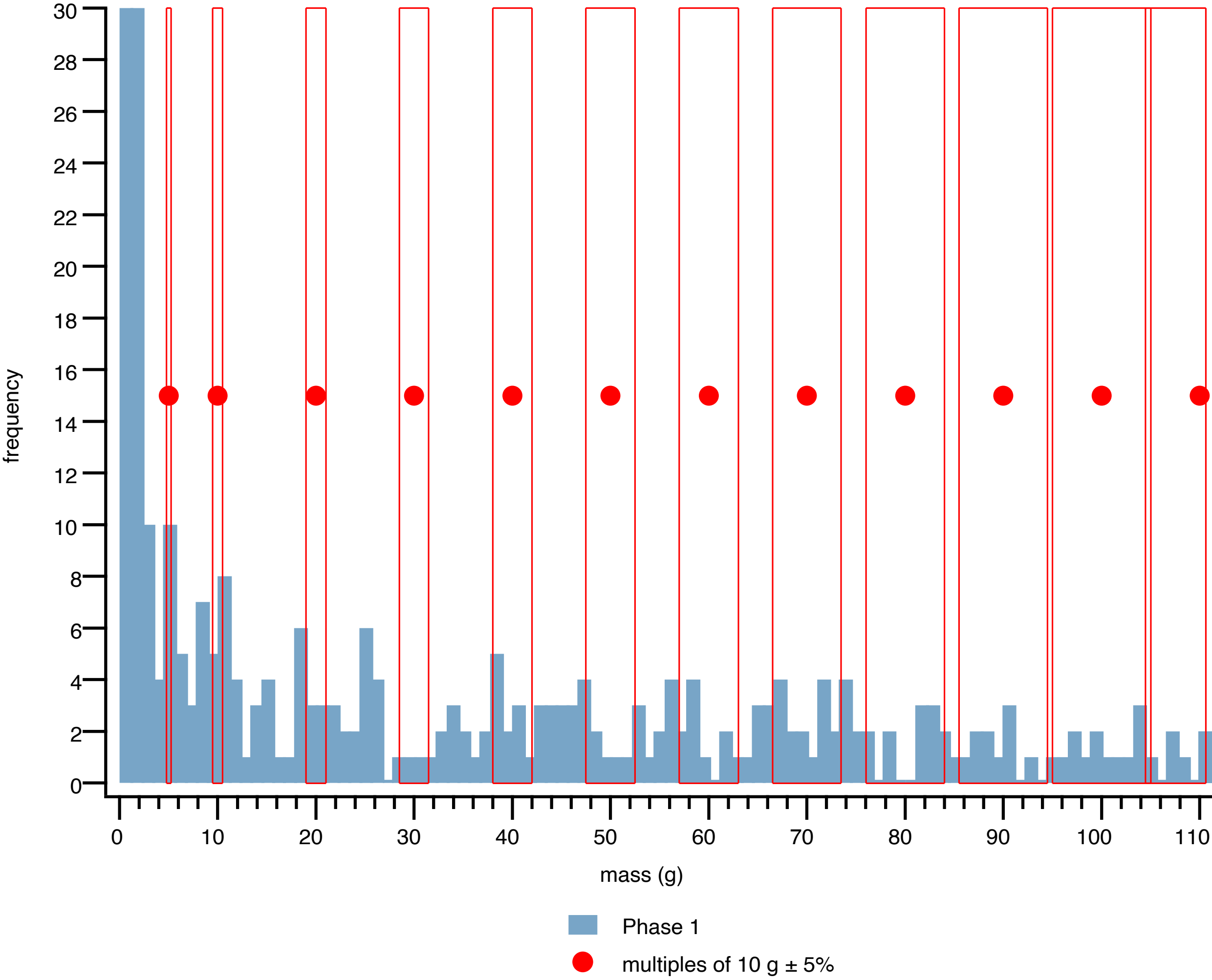
Theoretical Quantiles
Sample Quantiles
Density
Archaeological Sample - Phasde 1
Archaeological Sample - Phasde 2
Archaeological Sample - Phasde 3

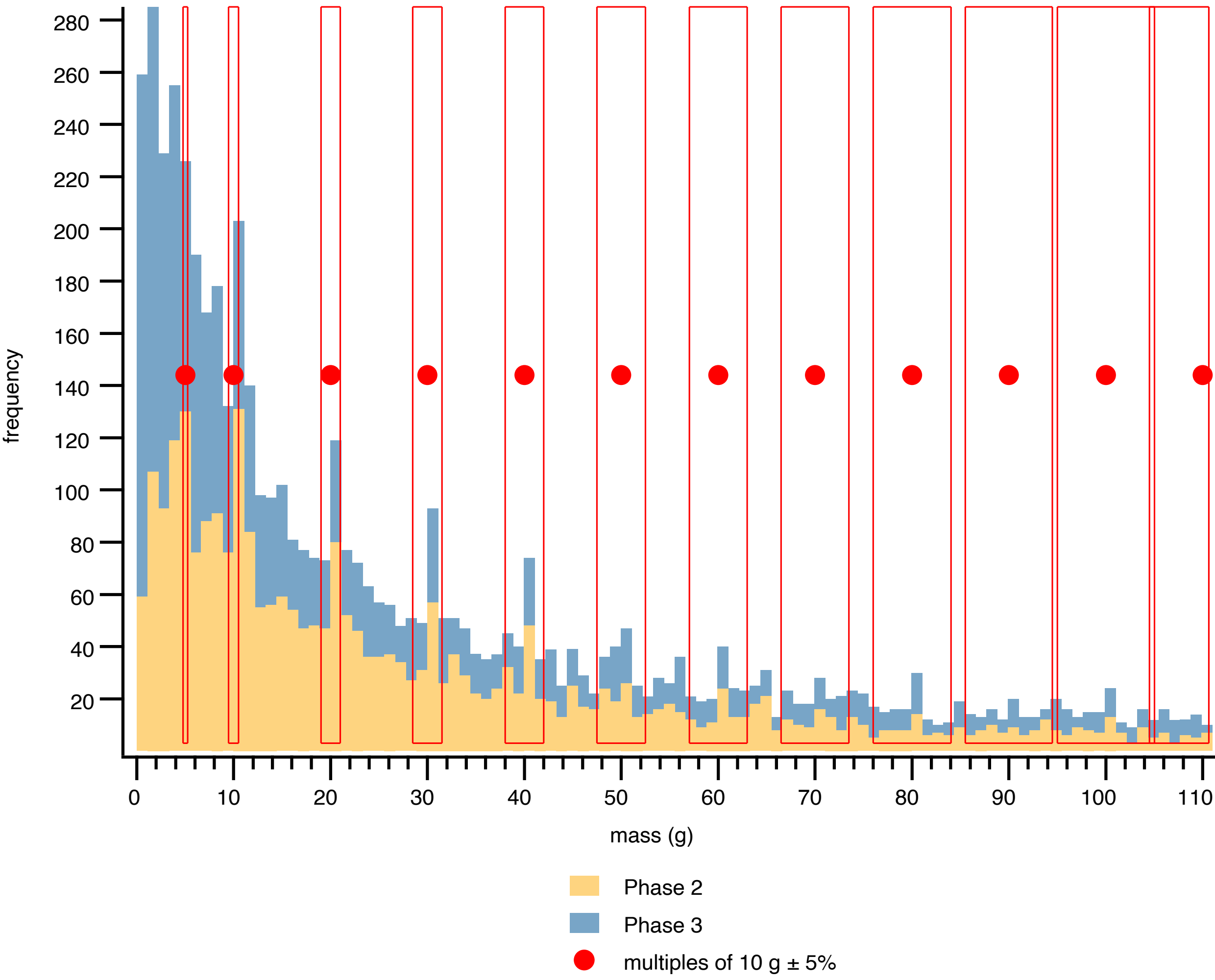

REMAINDER
A
B
C
price
CONSUMPTION
lognormal (expected)
SUPPLY
lognormal
STOCK
random

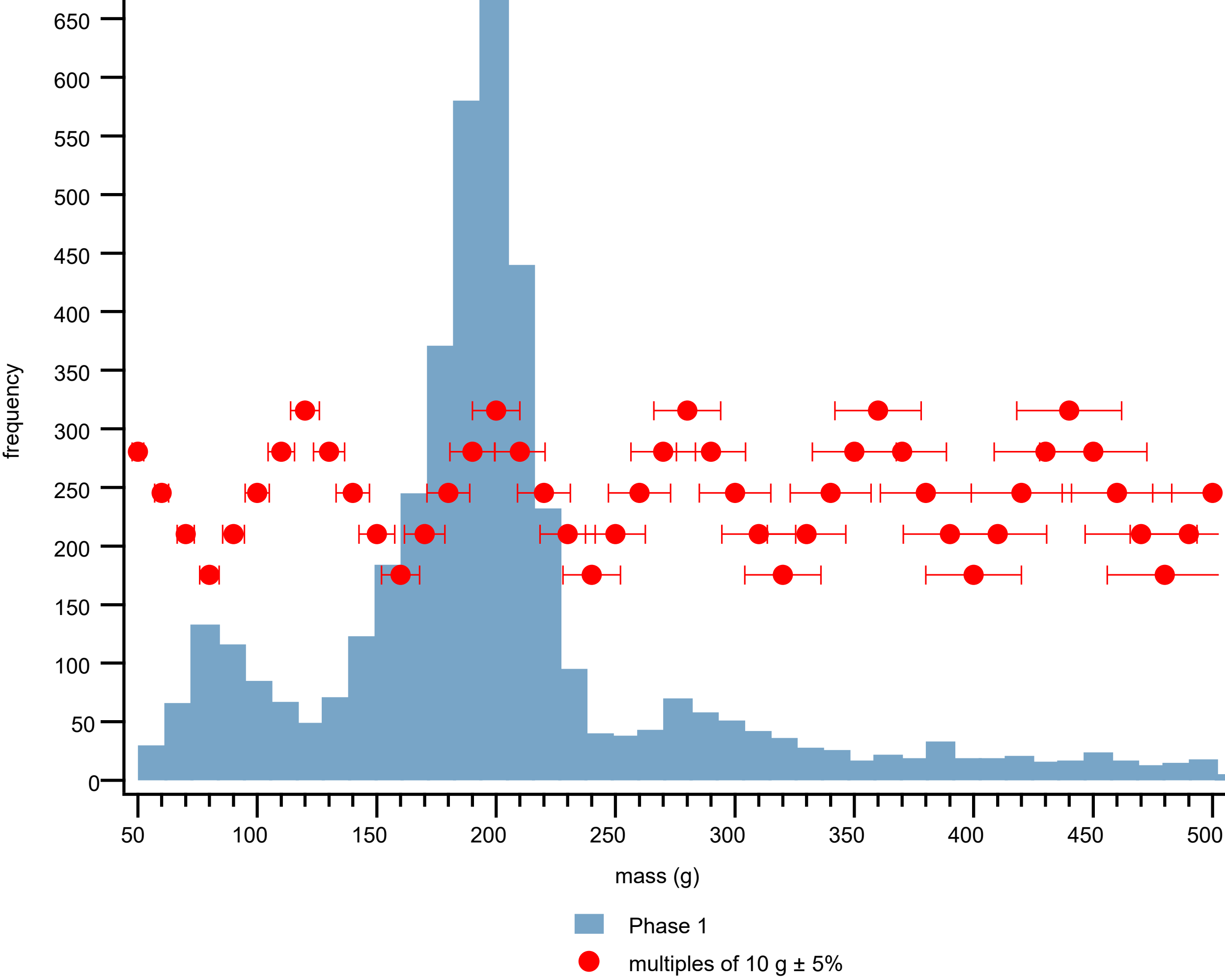

10^4
10^3
10^2
10^1
10^0
g
mina
CQA upper limit
shekel
CQA lower limit
shekel weights
fragments
complete
mina weights


Phase 1
Phase 2
Phase 3
phi(q)
quanta
Weights_n=16 (18)
Weights smooth
Weights_n=63 (134)
Weights smooth
Weights_n=41 (69)
Weights smooth
Phase 1
Phase 2
Phase 3
phi(q)
quanta
fragments_n=245 (396)
complete_n=2705 (4579)
fragments smooth
complete smooth
fragments_n=2462 (3355)
complete_n=809 (1111)
fragments smooth
complete smooth
fragments_n=1861 (3154)
complete_n=776 (1126)
fragments smooth
complete smooth

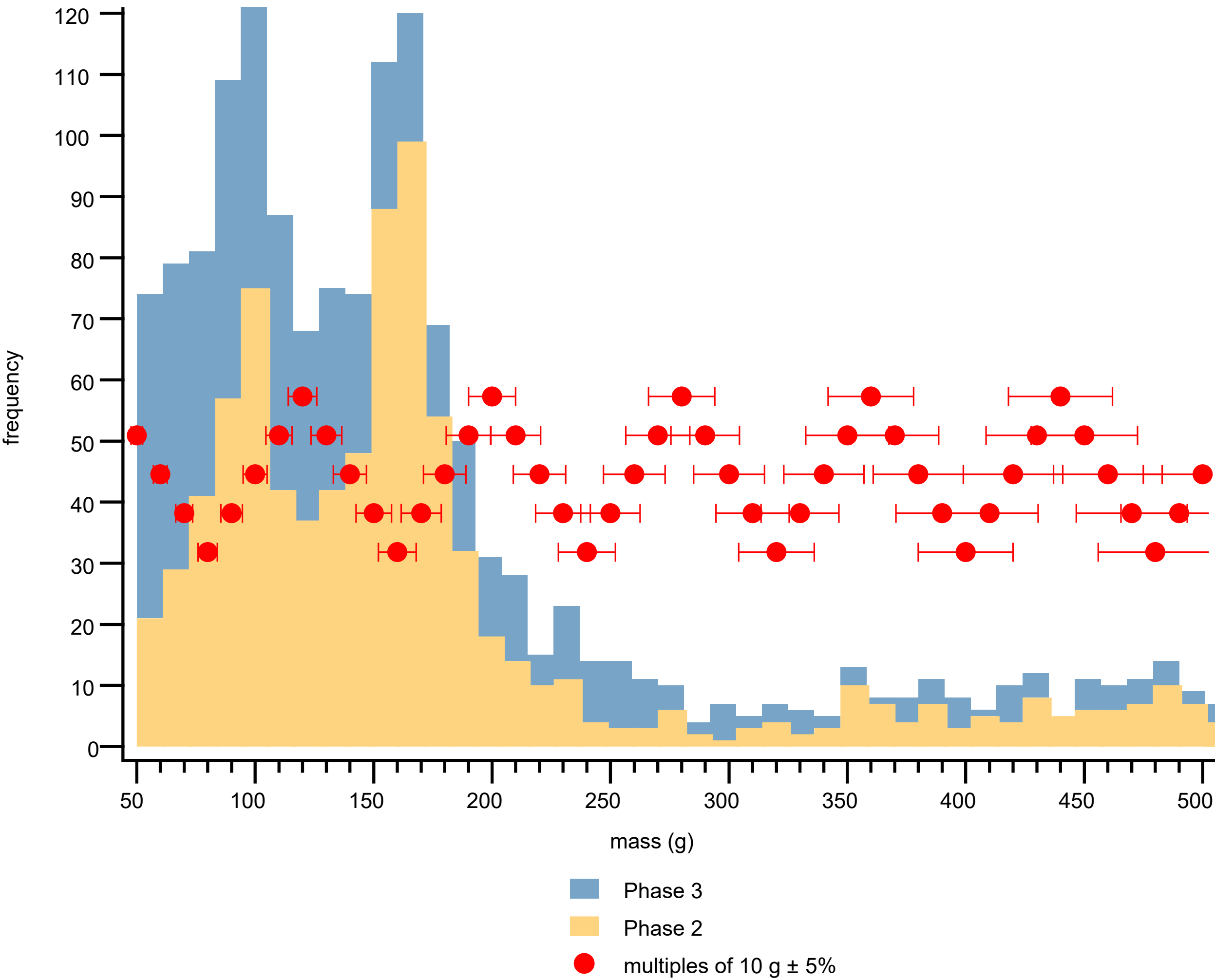

phi(q) balance weights
phi(q) bronze objects
quanta
4
3
2
1
0
-1
-2
-3
-4
6
4
2
0
-2
-4
-6
2
4
6
8
10
12
14
16
balance weights
bronze fragments
alpha 5% (bronze fragments)


frequency
mass (g)
Phase 1
multiples of 10 g ± 5%

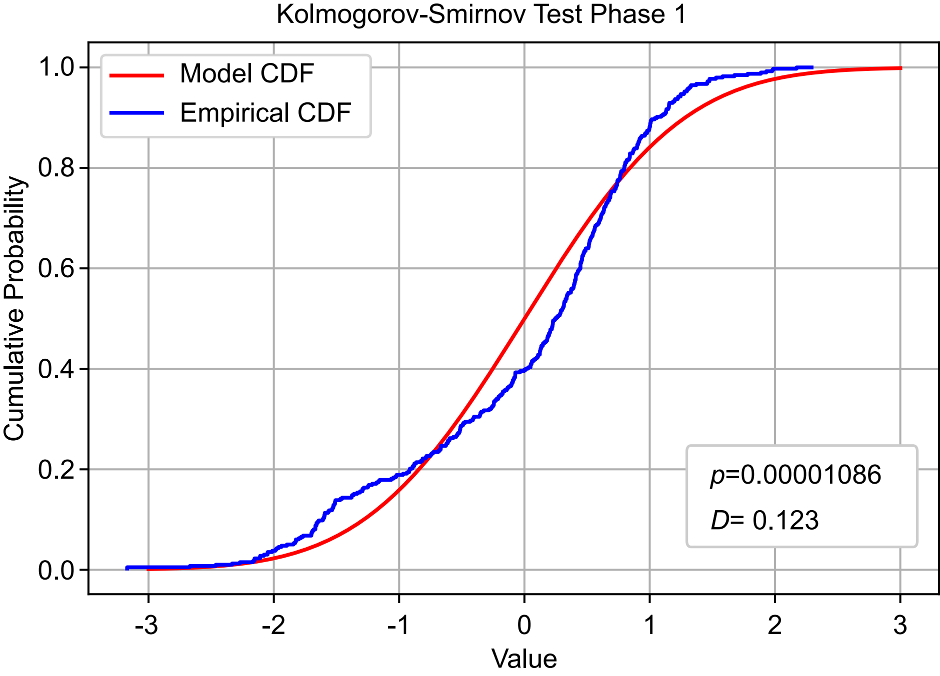

frequency
mass (g)
Phase 2
Phase 3
multiples of 10 g ± 5%

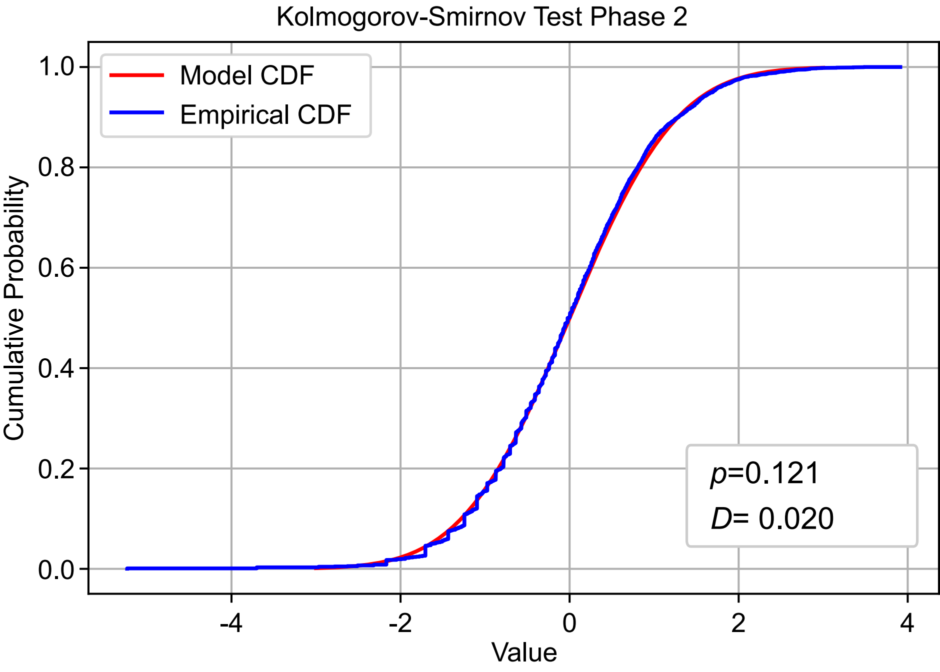


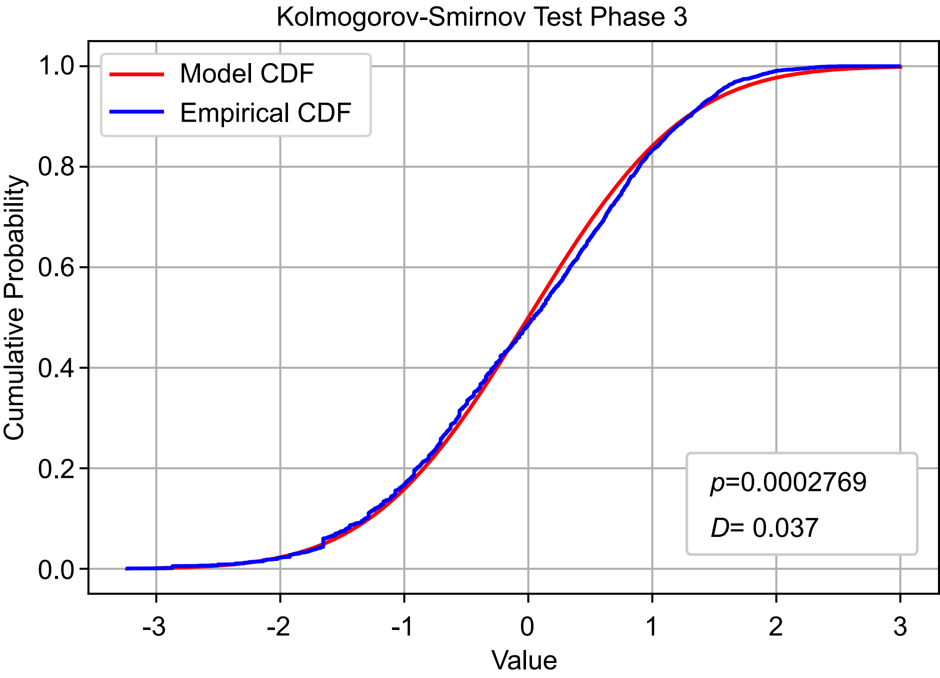
650
600
550
500
450
400
350
300
250
200
150
100
50
0
frequency
50
100
150
200
250
300
350
400
450
500
mass (g)
Phase 1
multiples of 10 g ± 5%

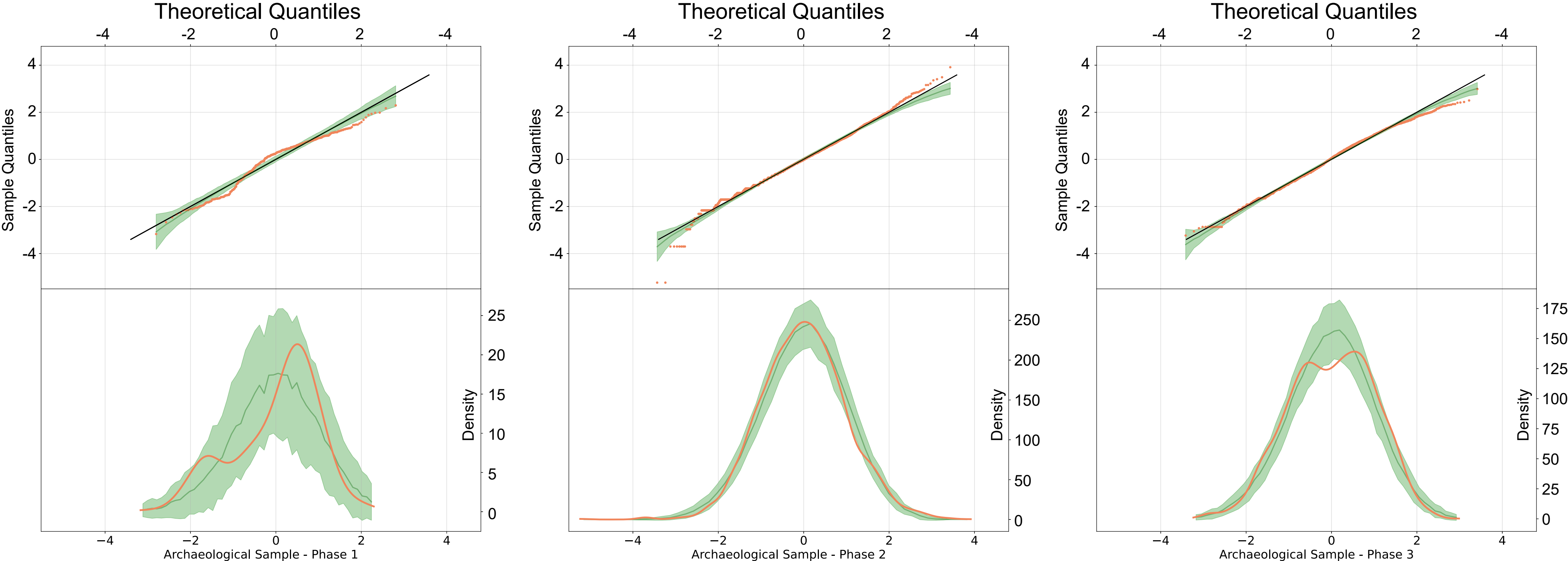


120
110
100
90
80
70
60
50
40
30
20
10
0
frequency
50
100
150
200
250
300
350
400
450
500
mass (g)
Phase 3
Phase 2
multiples of 10 g ± 5%


Kolmogorov-Smirnov Test Phase 1
Model CDF
Empirical CDF
p=0.00001086
D= 0.123
Cumulative Probability
Value


Kolmogorov-Smirnov Test Phase 2
Model CDF
Empirical CDF
p=0.121
D= 0.020
Cumulative Probability
Value


Kolmogorov-Smirnov Test Phase 3
Model CDF
Empirical CDF
p=0.0002769
D= 0.037
Cumulative Probability
Value


Theoretical Quantiles
Sample Quantiles
Density
Archaeological Sample - Phase 1
Archaeological Sample - Phase 2
Archaeological Sample - Phase 3

Two-Sample Kolmogorov-Smirnov (bootstrap - 1,000 cycles)

Scenario 1 - random fragmentation	**Phase 1**	**Phase 2**	**Phase 3**
Mean of p-values	0.172192	0.000085	0.000382
Standard Deviation of p-values	0.001515	0.000003	0.000014
Share (%) of p-values exceeding 0.05	75.6	0	0