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Inequality in relational wealth within the upper societal segment: evidence from prehistoric Central Europe

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While our understanding of long-term trends in material wealth inequality in prehistoric societies has expanded in recent decades, we know little about long-term trends in other dimensions of wealth and about social developments within particular societal segments. This paper provides the first evidence of inequality in relational wealth within the upper societal segment of a supra-regional network of communities in prehistoric Central Europe over the first four millennia BCE. To this end, we compiled a novel dataset of 5000 single-funeral burial mounds and employed burial mound volume as a proxy for the buried individual's relational wealth. Our analysis reveals a consistently high level of inequality among the buried individuals, showing a wave-like pattern with an increasing trend over time. Additionally, our findings show temporal shifts in the size of the upper societal segment. Based on a review of archeological and paleo-environmental evidence, the temporal change in inequality may be explained by technological progress, climate and population dynamics, trade and social networks, and/or sociopolitical transformations.

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Introduction

For decades, researchers have been trying to learn about the evolution of social inequality in humanity's deep past. Empirical advances have been made in understanding inequality in modern and preindustrial as well as ancient societies (Alfani, 2021; Milanovic, 2016; Piketty, 2014; Piketty and Saez, 2014; Scheidel, 2017; McGuire, 1983; Bogaard et al., 2019; Borgerhoff Mulder et al., 2009; Fochesato et al., 2019, 2021; Kohler et al., 2017; Windler et al., 2013). Especially our knowledge about the development and drivers of ancient inequality has greatly improved in recent years. But, the literature often focusses on explaining inequality in the entire society. To gain a comprehensive understanding of (ancient) inequality, however, it is also crucial to examine inequality within specific societal segments, such as the very rich or very poor.

Current research emphasizes the importance of understanding inequality dynamics within so-called "elites," as intra-elite inequality and conflicts can potentially destabilize entire societies (Turchin, 2023). However, such conflicts and substantial societal changes typically occur only every few decades. Therefore, adopting a long-term perspective and studying social dynamics in ancient societies can provide valuable lessons for the present and future.

At this point, we still lack long-run data on inequality within "elites" or, more broadly, within an "upper societal segment." Furthermore, when studying this segment, we need to look beyond material wealth inequality and explore other types of inequality. The reason is that members of an upper societal segment exert power not only through their material wealth but also through, for example, their social ties and networks.

In this paper, we take an initial step in providing long-run evidence from prehistorical Central Europe regarding the development of inequality within an upper societal segment. In particular, we focus our analyses on inequality in *relational wealth* and changes in the size of the upper societal segment. In this context, we consider the relational wealth of an individual as its endowment with social ties and networks (Borgerhoff Mulder et al., 2009). To study relational wealth inequality among individuals in prehistorical Central Europe, we constructed a dataset of ~5000 single-funeral burial mounds that date back to the first four millennia BCE. Central Europe is archeologically well studied, but a detailed quantitative assessment of inequality in the longue durée is still lacking.

The focal point of our inequality analyses is the volumes of the burial mounds, which we employ as proxies for the relational wealth of the buried individuals. We assume that the larger the volume of the burial mound, the greater the individual's relational wealth. In other words, an individual who possessed a large burial mound had a higher economic and political ability to mobilize people and resources within its (social) network to accomplish specific goals than an individual with a small burial mound. It is important to note that these networks were typically confined to local communities/societies and did not extend across the entire region of Central Europe. Nonetheless, we assume that the respective communities/societies were economically and socially highly interconnected, forming part of a supra-regional network. This perspective is supported by existing archeological evidence (Parker Pearson, 2003; Kristiansen and Larsson, 2005; Milisauskas, 2011; Kerig and Shennan, 2015; Furholt, 2021).

Despite potential variations in social–cultural formations within prehistoric societies, individuals with greater access to resources and networks constitute the upper societal segment. Of course, the proportion of individuals holding higher social status in comparison to the entire population may vary due to differences in social practices. However, as burial mounds were predominantly reserved for those individuals who had a high social status, these data offer us a unique opportunity to analyze inequality between those socially distinguished individuals that formed the upper societal segment of the mentioned supra-regional network (Capelle, 2000; Eggert, 1999). To analyze inequality among these individuals, we employ inequality indices such as the Gini index to the data. We interpret the resulting values as measures of inequality among buried individuals' leverage to make use of their resources and networks.

In addition to the burial mound data, we collected information on the number of individuals buried in flat and collective burials. From these data, we can estimate the share of individuals buried in burial mounds over time. This share gives us an idea about how many people were able to express their relational wealth via burial mounds. Or, to put it differently, this share tells us about the size of the upper societal segment.

Our analyses reveal two key findings about prehistoric inequality. First, there is a wave-like trend in the share of individuals who had sufficient relational wealth for the construction of a burial mound. This finding indicates a changing size of the upper societal segment in Central Europe over time. Second, the level of inequality in relational wealth between these individuals was high throughout the entire period. However, it was not constant but steadily changed with an increasing trend over time—especially during the last 1200 years BCE. From an archeological perspective, factors that help to rationalize our results are the establishment of new technologies and their social implications (Boserup, 1981; Childe, 1957; O'Brien and Shennan, 2010), improvement or deterioration of weather and climate conditions (Roberts, 1998; Erdkamp and Manning, 2021), changes in the size and composition of the population (Johnson, 1982; Bettencourt et al., 2007; Müller, 2013a; Zimmermann, 2012), the emergence and rearrangements of trade and social networks (Furholt, 2014; Feinman, 2017; Kristiansen et al. 2018), and shifts in the sociopolitical structure (Furholt et al., 2020; Kienlin and Zimmermann, 2012).

Burial mound volume as a proxy for relational wealth

Earth mounds are among the most well-known archeological structures in Europe (Harding, 2000; Johansen et al., 2004; Bourgeois, 2013). They represent a complex social practice involving economic, ideological, and political realities and are considered as the graves of individuals with a distinguished social status (Capelle, 2000; Assmann, 2013; Müller-Scheeßel, 2013; Endrigkeit, 2014; Osborne, 2014; Müller, 2018). To assess the social status of a buried individual, we use the volume of its burial mound as a proxy for its relational wealth (Borgerhoff Mulder et al., 2009; Beck and Quinn, 2023). The relational wealth of an individual represents its economic and political ability to mobilize people and resources in its (social) network to achieve certain goals. Since the buried individual is dead at the time when the burial mound is erected, we consider the erection as a posthumous form of its relational wealth. Furthermore, studies on ethnoarcheological documented communities show that constructing a monument often involves a larger kinship group that extends beyond the individual household (Jeunesse, 2018; Miller, 2021; Wunderlich et al., 2021). In this context, the construction of a burial mound can also be understood as a social signal symbolizing a long-term investment of the deceased and the associated group (Bliege Bird and Smith, 2005; Quinn, 2019). Hence, burial mounds demonstrated the economic and political ability of the individual and group to compete and collaborate with other individuals and groups in the local and regional network (Parker Pearson, 2003; Leach, 1979).

In our analyses, we only use burial mounds dedicated to a single individual. Therefore, it is possible to interpret the construction of a burial mound as directly related to an individual's relational wealth. Hence, the larger the burial mound, the wealthier, more powerful, and the better integrated the buried individual into local and regional networks. Furthermore, we use a burial mound's volume instead of its floor area to measure relational wealth. The reasoning is as follows: If we assume that the effort required to build a burial mound is proportional to its floor area, this will mean that a burial mound with a large floor area would have the same height as one with a small floor area. Given the observed shapes of burial mounds, this relationship does not seem reasonable. Since we cannot observe the volume of each burial mound in the dataset, we make archeologically reasonable assumptions about a burial mound's shape to compute the respective volumes. We explain the computation procedure in the methods section in more detail.

Measuring prehistoric inequality with burial mound data

To construct our dataset, we collected information on the size of burial mounds from extensive archeological catalogs. Our dataset provides information on 4986 burial mounds in Central Europe. It covers the first four millennia BCE and includes burial mounds from the Neolithic up until the appearance of the Romans in Central Europe. Additionally, we collected data on the prevalence of individuals buried in flat and collective burials. In our analysis, we measure inequality in relational wealth between individuals in the entire geographic area of Central Europe, which yields the most time-granular perspective. Although our dataset's spatial granularity allows for subregional analyses, we leave them for future research. Such analyses require a thorough discussion of the regional archeological background, which is beyond the scope of this article. SI, Sections 1 and 2 display all variables included in our dataset and the additional data, along with a concise description of their meaning. The references of the primary archeological catalogs from which we compiled the data are available in SI, Section 8.

Given that the dating intervals of the burial mounds vary between 10 and 4700 years, we decided to limit our analysis to burial mounds with a maximum dating interval of 600 years. This restriction reduces the size of our dataset, but it ensures more precise results. Nonetheless, it is worth noting that limits beyond 600 years do not significantly alter our findings (see SI, Section 7). Hence, our results are mainly driven by the well-dated burial mounds. Finally, we split our observation period into intervals of 200 years and assign each burial mound to one of the intervals according to the average of the initial and final value of its dating interval. The choice of 250- and 300-year intervals, again, does not substantially alter the results (see SI, Sections 5 and 6).

Figure 1 displays maps with the spatial location of the burial mound sites in each 200-year interval. To avoid confusion about small sample sizes, we note that some sites consist of multiple burial mounds. However, for the intervals 0–200 BCE, 2800–3000 BCE, and 3000–3200 BCE, the number of burial mounds is too low for a credible analysis (see SI, Section 4). Although the burial mound sites are spatially dispersed within the 200 intervals, we consider the entire study region to be characterized by high economic and social connectivity (Parker Pearson, 2003; Kristiansen and Larsson, 2005; Milisauskas, 2011; Kerig and Shennan, 2015; Furholt, 2021). Furthermore, we view the communities within this region as parts of a supra-regional network that spans across Central Europe.

To assess the degree of inequality in relational wealth between the individuals of the upper societal segment of the supra-regional network, we use the Gini index and indices from the class of Generalized Entropy Measures (Kohler et al., 2017; Windler et al., 2013; Cowell, 2000).[1] It is important to emphasize that the estimates obtained for the indices are subject to statistical uncertainty. A typical method to calculate the standard error of an index is the use of asymptotic theory, notably bootstrapping. In the present dataset, however, the summary statistics in SI, Section 4 show that we face "heavy-tailed" distributions, a reason why bootstrapping is not sufficient (Davidson and Flachaire, 2007; Cowell and Flachaire, 2015; Dufour et al., 2019). We, therefore, apply permutation tests to assess the statistical significance of differences between two inequality estimates (Dufour et al., 2019).

Methods

Computation of a Burial Mound's Volume from its Ground Area. As argued in the section "Burial Mound Volume as a Proxy for Relational Wealth," we use a burial mound's volume instead of its floor area as a proxy for the buried individual's wealth. Since we cannot observe the volume of each burial mound, we employ a non-linear transformation of its floor area and information about its shape to reconstruct the volume. It is important to mention that the dataset contains burial mounds of five different geometric shapes (viewed from a bird's eye view): round, round-oval, oval, rectangular, and trapezoid. For the transformation, we summarize the shapes round, round-oval, and oval as "round" and the shapes rectangular and trapezoid as "rectangular."

Starting with round-shaped burial mounds, the procedure is as follows: Let r be the radius of a circle and a sphere, A be the area of the circle, and V be the volume of the sphere. Then

$$A = \pi r^2$$

and

$$V = \frac{4}{3}\pi r^3.$$

Supposing that the volume of a round-shaped burial mound can be approximated by the formula of a hemisphere

$$V_{\text{round}} = \frac{2}{3}\pi r^3$$

and that the height of the burial mound is proportional to its radius, then reformulating V_{round} yields:

$$V_{\text{round}} = \frac{2}{3}\pi r^3 = \frac{2}{3}\frac{\pi^{0.5}}{\pi^{0.5}}\pi r^3 = \frac{2}{3\pi^{0.5}}\pi^{1.5} r^3 = \frac{2}{3\pi^{0.5}}\left(\pi r^2\right)^{1.5} = \frac{2}{3\pi^{0.5}}A^{1.5}.$$

Multiplying the volume by an arbitrary constant would not influence the outcomes of the inequality indices in this paper since they all satisfy the scale invariance axiom (Cowell, 2000). Hence, if all round-shaped burial mounds have a hemisphere shape, transforming the floor area of each burial mound by an exponent of 1.5 yields its volume.

Concerning rectangular-shaped burial mounds, the procedure is very similar. Let l be the length of a rectangular, w its width, A its area, and let V be the volume of a corresponding cuboid with length l, width w, and height h. Then

$$A = lw$$

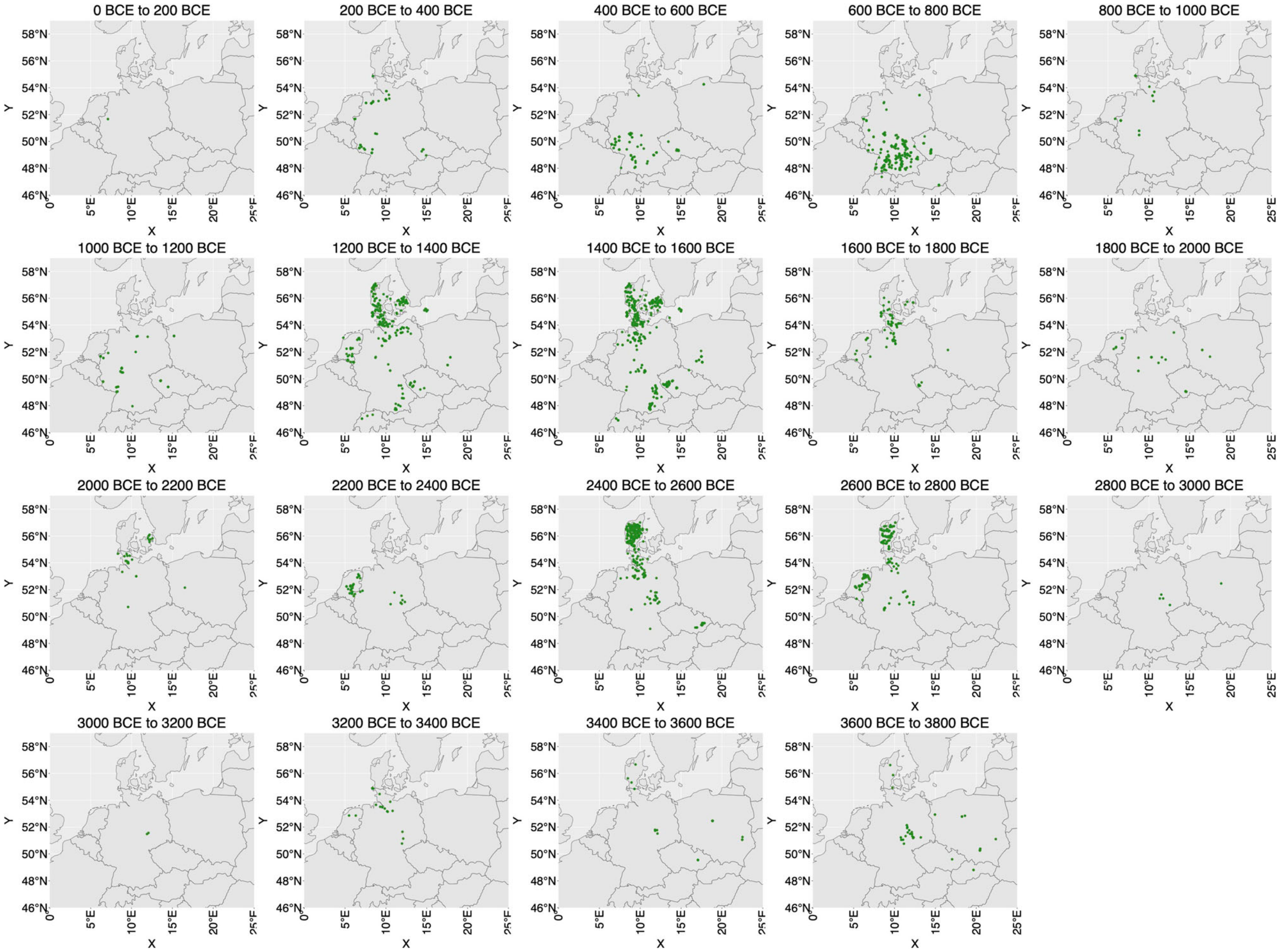

Fig. 1 Spatial distribution of the burial mound sites in each of the 200-year intervals of the analysis. A green dot shows the geographical position of a burial mound site.

and

$$V = lwh.$$

Furthermore, suppose that the volume of a cuboid V_{rec}—which corresponds to an area A_{rec}—approximates the volume of a rectangular-shaped burial mound. Also, assuming that the length of this cuboid is proportional to its width $\left(l := c_1 w\right)$, and that the height of the cuboid is proportional to its width $(h := c_2 w)$, then

$$A_{rec} = \underbrace{c_1 w}_{l} \cdot w = c_1 w^2$$

and

$$A_{rec} = \underbrace{c_1 w}_{l} \cdot w \cdot \underbrace{c_2 w}_{h}$$

Reformulating V_{rec} yields

$$V_{rec} = \underbrace{c_1^{0.5}}_{c_1^{0.5}} \underbrace{c_1 w}_{l} \cdot w \cdot \underbrace{c_2 w}_{h} = c_1^{1.5} w^3 \frac{c_2}{c_1^{0.5}} = \left(c_1 w^2\right)^{1.5} \frac{c_2}{c_1^{0.5}} = A_{rec}^{1.5} \frac{c_2}{c_1^{0.5}}.$$

Again, multiplying the volume by an arbitrary would not matter for the computation of the inequality indices. Hence, if all rectangular-shaped burial mounds have a cuboid shape, with their length and height proportional to their width, transforming the floor area of each burial mound by an exponent of 1.5 yields its volume as well.

Mathematical formulas for the inequality indices and their asymptotic standard errors. The following three expressions present formulas for computing the indices from the class of generalized entropy measures $\left(I_c, I_0, I_1\right)$ the Gini index (G), and the normalized Gini index (G^*) Cowell (2000).

$$I_c = \frac{1}{n} \frac{1}{c(c-1)} \sum_{i=1}^{n} \left(\left(\frac{x_i}{\bar{x}} \right)^c - 1 \right) \forall c \neq 0, 1$$

$$I_0 = \frac{1}{n} \sum_{i=1}^{n} \log\left(\frac{\bar{x}}{x_i} \right) \text{ for } c = 0$$

$$I_1 = \frac{1}{n} \sum_{i=1}^{n} \left(\frac{x_i}{\bar{x}} \right) \log\left(\frac{x_i}{\bar{x}} \right) \text{for } c = 1$$

$$G = \frac{1}{2n^2 \bar{x}} \sum_{i=1}^{n} \sum_{j=1}^{n} \left| x_i - x_j \right|$$

$$G^* = \frac{n}{n-1} G$$

The notation is as follows: n denotes the number of burial mounds in the sample, i and j specific burial mounds, x_i and x_j the volume of burial mounds i, j, $\bar{x}$ the arithmetic mean of x, and c a sensitivity parameter.

The following expression states the formula for the asymptotic standard error (ASE) that is valid for all indices from the GEM class (Cowell and Flachaire, 2015).

$$ASE(I_c) = \sqrt{\frac{1}{n^2}\sum_{i=1}^{n}\left(Z_i - \bar{Z}\right)^2}$$

Z_i denotes a term that differs for particular values of the sensitivity parameter c, and $\bar{Z}$ is the average of all Z_i. Using the same notations as in the previous formulas, the following three expressions give the respective Z_i for different values of c.

$$Z_i = \frac{1}{c^2 - c}\left(\frac{x_i}{\bar{x}}\right)^c - c\left(\frac{x_i}{\bar{x}}\right)\left(I_c + \frac{1}{c^2 - c}\right)\forall c \neq 0, 1$$

$$Z_i = \left(\frac{x_i}{\bar{x}}\right)\log(x_i) \text{ for } c = 0$$

$$Z_i = \left(\frac{x_i}{\bar{x}}\right)\left(\log\left(\frac{x_i}{\bar{x}}\right) - I_1 - 1\right) \text{for } c = 1$$

Regarding the normalized Gini index, the subsequent expression displays a formula for its asymptotic standard error (ASE) with the notation being as before (Cowell and Flachaire, 2015).

$$ASE(G^*) = \sqrt{\frac{1}{(n\bar{x})^2}\sum_{i=1}^{n}\left(Z_i - \bar{Z}\right)^2}$$

Correspondingly, the next expression defines the formula of the Z_i, where $x_{(i)}$ denotes the ith element of the ordered sample. The observations in the ordered sample are ranked by ascending magnitude of their burial mound volume.

$$Z_i = -(G^* + 1)x_{(i)} + \left(\frac{2i - 1}{n}\right)x_{(i)} - \frac{2}{n}\sum_{j=1}^{i} x_{(j)}$$

Procedure of performing permutation tests. A primary methodological objective of this paper is to present a suitable tool for testing the statistical significance of a difference in two values of an inequality. In the presence of heavy-tailed distributions, the most appropriate tool for this exercise is permutation tests (Dufour et al., 2019). The theoretical foundations of the permutation test date back to the early 20th century (Pitman, 1937), but the recent work of Dufour et al. (2019) demonstrates their superiority in testing differences in inequality. Therefore, this section aims to provide a step-by-step procedure for conducting permutation tests based on their work. Concerning more detail on the method's technical foundations, we refer to the respective paper.

Suppose there are two populations, A and B. For example, population A could be the population of all burial mounds in the Neolithic in Central Europe, while population B could be the population of all burial mounds in the Bronze Age in Central Europe. The primary purpose lies in determining if the degree of inequality differs between these two periods. To measure the degree of inequality, we can use an inequality index θ. Hence, the "true" population degree of inequality in the Neolithic is θ_A and in the Bronze Age θ_B. However, since it is impossible to observe the entire population of burial mounds in each period, we cannot determine θ_A and θ_B. Thus, both values are unknown. Therefore, relying on observable sample data, we need to estimate them to get an idea about their values. The vector $X_A = \left(x_1^A, x_2^A, \ldots, x_m^A\right)$ contains the sample data from the Neolithic, and the vector $X_B = \left(x_1^B, x_2^B, \ldots, x_n^B\right)$ the sample data from the Bronze Age. There are m burial mounds in the sample X_A and n burial mounds in the sample X_B. The elements $x_1^A, x_2^A, \ldots, x_m^A$ are the corresponding volumes of observed burial mounds in the Neolithic, and the elements $x_1^B, x_2^B, \ldots, x_n^B$ are the corresponding volumes of observed burial mounds in the Bronze Age. Ideally, these samples are representative of their respective populations. Using the volumes in each sample, we can compute $\hat{\theta}_A$ and $\hat{\theta}_B$, where $\hat{\theta}_A$ is the degree of inequality in the sample X_A and $\hat{\theta}_B$ the degree in sample X_B. Both $\hat{\theta}_A$ and $\hat{\theta}_B$ are estimates of the true but unknown population degree of inequality. From this perspective, it is evident why statistical uncertainty surrounds the estimates $\hat{\theta}_A$ and $\hat{\theta}_B$ and why computing the difference between $\hat{\theta}_A$ and $\hat{\theta}_B$ does not answer the question if the degree of inequality between the population differs. A more appropriate answer to this question is to perform hypothesis testing using, for example, permutation tests. The most appropriate permutation test for testing differences in inequality proceeds as follows:

1. Set up a pair of hypotheses: $H_0 : \theta_A = \theta_B$ vs. $H_1 : \theta_A \neq \theta_B$. The null hypothesis H_0 states that employing inequality index θ to assess the degree of inequality in population A and B, inequality does not differ between them. In contrast, the alternative hypothesis H_1 states the degree of inequality differs.
2. To test this pair of hypotheses, the permutation test uses the sample data from X_A and X_B. To guarantee the asympotitc validity of the permutation test, it is necessary to scale the samples X_A and X_B using their respective sample means $\bar{x}_A$ and $\bar{x}_B$. Hence, the scaled samples are $X_A = \left(\frac{x_1^A}{\bar{x}_A}, \frac{x_2^A}{\bar{x}_A}, \ldots, \frac{x_m^A}{\bar{x}_A}\right)$ and $X_B = \left(\frac{x_1^B}{\bar{x}_B}, \frac{x_2^B}{\bar{x}_B}, \ldots, \frac{x_m^B}{\bar{x}_B}\right)$.
3. Under H_0, it does not matter from which sample the data for computing $\hat{\theta}_A$ and $\hat{\theta}_B$ stems. Therefore, the permutation test merges X_A and X_B to obtain a combined sample $X_C = \left(\frac{x_1^A}{\bar{x}_A}, \frac{x_2^A}{\bar{x}_A}, \ldots, \frac{x_m^A}{\bar{x}_A}, \frac{x_1^B}{\bar{x}_B}, \frac{x_2^B}{\bar{x}_B}, \ldots, \frac{x_m^B}{\bar{x}_B}\right)$. X_C contains $m + n$ burial mound volumes.
4. The next exercise is to permute X_C. In total, there exist $(m + n)!$ different permutations.
5. The problem is that the larger the sample sizes m and n, the larger the number of possible permutations. Therefore, the permutation test randomly draws K of these $(m + n)!$ permutations without replacement. Hence, including the initially combined data X_C, there are $K + 1$ permutations available for the analysis.
6. Subsequently, we need to choose a suitable test statistic for testing the difference in the degree of inequality between the two populations. In this case, $S = \frac{\hat{\theta}_A - \hat{\theta}_B}{\sqrt{V(\hat{\theta}_A) + V(\hat{\theta}_B)}}$ is an appropriate test statistic. $V(\hat{\theta}_A)$ and $V(\hat{\theta}_B)$ are estimates (asymptotic/bootstrap) of the variance of $\hat{\theta}_A$ and $\hat{\theta}_B$. If the samples are dependent, it is necessary to adjust the denominator by including the covariance of the samples.
7. Using the formula for the test statistic from 6., as well as the data from the original samples X_A and X_B, the permutation test computes the observed test statistic S_{obs}.
8. The next step splits each of the K permutations into two samples of size m and n. For example, the first m burial mound volumes form the elements for the sample of population A, whereas the remaining n burial mound volumes form the elements for the sample of population B.
9. The computation of the test statistic from 6—using the data from the split samples of the K permutations—yields K values of the test statistic.
10. Finally, comparing the values of the K test statistics with the initially observed test statistic S_{obs} yields the permutation test's p-value. The formula for the p-value is the following: $p - \text{value} = 2\min\left\{\frac{\sum_{j=1}^{K} I(S_j \leq S_{\text{obs}}) + 1}{K+1}, \frac{\sum_{j=1}^{K} I(S_j \geq S_{\text{obs}}) + 1}{K+1}\right\}$. S_j is the

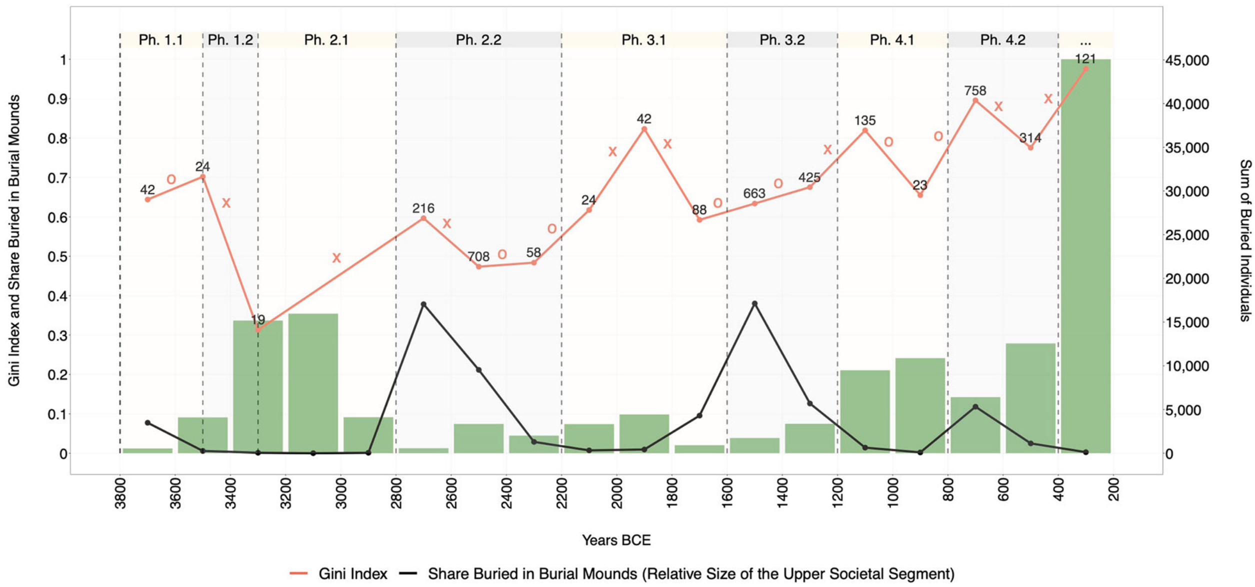

Fig. 2 Development of inequality in relational wealth between the members of the upper societal segment using time intervals of 200 years. The red and black lines connecting inequality estimates and the shares of individuals buried in burial mounds for consecutive time slices are linear interpolations and not actual observations. A "x" on top of each line connecting the inequality estimates indicates if the difference in the estimates between two periods is statistically significant (p-value < 0.1). In contrast, a "o" indicates a statistically insignificant difference (p-value ≥ 0.1). The numbers on top of the inequality estimates show the sample size. The green bars represent the sum of buried individuals (burial mounds, flat graves, and collective graves) in the respective time intervals captured by our data. The black line displays the share of individuals buried in burial mounds, which gives us an idea about the relative size of the population's upper societal segment and social mobility and structures. SI, Sections 4 and 7 contain the numerical results for this figure.

test statistic's value corresponding to permutation K and $I(\cdot)$ is an indicator function taking on the value 0 if the condition within the brackets is not true and 1 if the condition is true.

In addition to the importance of rescaling the samples, there is another condition under which permutation tests are asymptotically valid. This condition holds when the sample sizes are equal, or the underlying distributions have the same asymptotic variance. However, it has been shown that even for very unequal sample sizes and heavy-tailed distributions, permutations tests outperform bootstrap and asymptotic testing procedures (Dufour et al., 2019). It has also been shown that permutation tests are superior to other testing procedures from a size and power perspective (Dufour et al., 2019). Therefore, they are the best option for testing differences in inequality in our dataset.

A time-granular perspective on social inequality

Figure 2 shows the results of the temporally fine-grained analysis of inequality in relational wealth between individuals of the upper societal segment, the sum of buried individuals (individuals buried in burial mounds, flat burials, and collective burial), and the share of individuals buried in burial mounds. Since the results are very similar across the four inequality indices (see SI, Section 4), we discuss our findings considering the Gini index. We use the share of individuals buried in burial mounds to get an idea about the size of the upper societal segment. To calculate this share, we divide the number of single-funeral burial mounds by the sum of individuals buried in collective and flat burials and burial mounds.

Studying our results and accompanied archeological evidence, we recognize a repeating, wave-like pattern in the share of individuals buried in burial mounds over time. The pattern consists of two phases. In the initial phase, only a few individuals were buried in burial mounds, whereas in the second phase, many more were buried in burial mounds. In each of the two phases, we observe fluctuations in inequality in relational wealth between the individuals of an upper societal segment that follow an increasing, overarching trend. The pattern emerges first from about 3800 BCE to 3300 BCE and second from 3300 BCE to 2200 BCE. Then, the third and fourth time, it emerged from roughly between 2200 BCE and 1200 BCE and from 1200 to 200 BCE. We rationalize the context of the pattern and its two phases based on the rich corpus of literature on the emergence of (ancient) inequality and social stratification (Borgerhoff Mulder et al., 2009; Kohler et al., 2017; Kienlin and Zimmermann, 2012; Lenski, 1966; Price and Feinman, 1995, 2010; Stanish, 2017; Thomas and Mark, 2013):

The pattern's first phase (1) is characterized by the occurrence of innovations, such as new production techniques and technologies in the form of new tools, metals, or crops. This occurrence often goes along with the emergence of new or shifting over-regional trade and exchange networks. Goods being exchanged over such networks are not only commodities and resources but also knowledge. Initially, only a few people take pivotal positions in these networks and make use of the incoming innovations. The management of the flow of information and resources in their network also helps these few people consolidate their social position over time. This setup can then be used to further gain economic and political power. As a result, the relational (and material) wealth of those individuals steadily increases and makes them part of the upper societal segment. Those who have nodal positions in regional and inter-community exchange networks are likely part of a local *managerial elite* (Stanish, 2017). At the end of phase (1) and during the transition process to phase (2), the innovation becomes established and is more widely used in society; but key network positions are still held by a few individuals.

At the start of the pattern's second phase (2), disruptive events such as migration, cultural transformation, or environmental change trigger a rearrangement of large-scale trade and exchange networks established in phase (1). This rearrangement offers

Table 1 Overview of the occurrences of the proposed patterns with 2 phases and the corresponding size of the upper societal segment (given by the share of individuals buried in burial mounds; black line in Fig. 2), inequality in relational wealth between the individuals of the upper societal segment, network structure, and innovations/triggers that led to transformations in social structures and networks (see the text for more details).

Pattern	Phase	Dating BCE	Size in upper societal segment	Inequality in upper societal segment	Network structure	Innovation/triggers
P1	Ph 1.1	3800–3500	Medium	High	More centralized	• Animal traction and the ard • Horticulture • Copper metallurgy
	Ph 1.2	3500–3300	Small	Low	More localized	• Bond −5.9 ka climate event • Agriculture • Wheel and the increasing use of animal traction in transport and agriculture
P2	Ph 2.1	3300–2800	No data[a]	No data[a]	More centralized	• Cattle: draft animal, dairy production • Long distance trade peak jade (west)/ copper tools (east)
	Ph 2.2	2800–2200	Large	Medium	More localized	• New communication networks • Influx of steppe individuals • Gender differentiation
P3	Ph 3.1	2200–1600	Small	High	Centralized	• Bond −4.2 ka climate event • Tin bronze technology
	Ph 3.2	1600–1200	Large	Medium	More localized	• Tin bronze technology generally established • Societal transformation in the East-Mediterranean • Changes in long-distance trade networks
P4	Ph 4.1	1200–800	Small	High	More centralized	• Collapse of Mediterranean societies • Changes in long-distance trade networks • Millet • Horse and chariot • Ideological changes (cremation as burial rite, bird symbolism)
	Ph 4.2	800–400	Medium	Very high	Localized with central hubs	• Iron metallurgy • Division of land • Mediterranean networks
P5?	Ph 5.1?	400–?	Small	Very high	Localized with central hubs	• Early monetary economy • Oppida

[a]Due to collective burial tradition, our proxy is not valid here. Based on the increased size differentiation of collective burials, we expect more inequality between burial communities (Müller, 2019; Wunderlich et al., 2019).

more individuals the opportunity to install their own and more localized networks. These networks are large enough for individuals to accumulate sufficient relational wealth that separates them from individuals from other parts of society. However, there are still individuals who can take pivotal positions in aggregated localized networks. These positions allow them to accumulate a high level of relational wealth.

This two-phase pattern repeats with the occurrence of another set of innovations and can be accelerated due to advances in transportation and infrastructure. Over time, the spread of certain innovations raises agricultural productivity, which can increase overall prosperity and might induce changes in population size (Turchin et al., 2022). Throughout these two phases, changes in technology, prosperity, and population size might result in competition between the individuals of the upper societal segment to aspire to more influence. All these changes may alter the pace of interaction within and the density of networks, which lead to increasing, but fluctuating levels of inequality in relational wealth. A comprehensive overview of our proposed patterns is described in the following paragraphs and summarized in Table 1. The trends in network structures shown in Table 1 are derived from the modeled size of collectively acting groups (Zimmermann, 2012), the influences of the innovations and transformation triggers listed in Table 1, and the findings of the cited works.

The first occurrence of the pattern (P1, 3800–3300 BCE) started with the emergence of new agricultural technologies such as animal traction and the ard around 3800–3400 BCE (Bakker et al., 1999; Whitehouse and Kirleis, 2014). The first phase (Ph 1.1, 3800–3500 BCE) is connected to long and round burial mounds with considerable size differences, which explain the high values of the Gini index. However, the large inequality estimates in the North and Central region of our research area partly contradict our views on the character of these Neolithic societies (Müller, 2001). Instead, they correspond to a higher degree of social stratification and are consistent with the unexpected extent of regional cooperating networks (Sørensen, 2014). In addition to changes in the subsistence economy, there were advances in copper metallurgy, and early copper items became valuable prestige goods (Brozio et al., 2023).

The second phase (Ph 1.2) dates between 3500 and 3300 BCE, and due to the low numbers of burial mounds and their decreased differentiation, a low Gini index is measured. A climatic cold event (Bond −5.9 ka climate event), dating around 3500 BCE, probably affected Central European societies as decreases in indicators of human activity show (Kolář et al., 2022; Bond et al., 2001; Heitz et al., 2021; Parkinson et al., 2021). Furthermore, it is reasonable to assume that the technology of the wheel and the increasing use of animal traction in transport and agriculture became established around 3500–3400 BCE (Klimscha, 2017;

Mischka, 2022). In contrast to other phases, a collective burial tradition emerged in our research area (northern parts) or burials in general became less visible (central part). Relational wealth, in this phase, was less attached to single individuals as labor investments were mostly assigned to structures of communal character, such as collective megalithic graves. However, it is reasonable to expect communication of economic and relational wealth between communities or extended sociopolitical groups through the erection of collective building endeavors (Gebauer, 2014; Wunderlich, 2019). The megalithic graves between 3500 and 3300 BCE show differentiation in size, respectively, in labor investment, but lower compared to earlier long barrows. Furthermore, there was an increase in the number of burial monuments (Müller, 2019; Wunderlich, 2019). The size of collective acting groups, compared to the preceding phase (Ph 1.1), decreased (Zimmermann, 2012).

Especially between 3600 and 3000 BCE, megalithic tombs were built in Northern Central Europe, which were used for collective burials of lineages or other sociopolitical groups (Schulz Paulsson, 2016). This raises the question of whether ideology played a role in the adoption or subsequent abandonment of collective burial practices (Müller, 2010; Brozio et al., 2019). To compute the sum of buried individuals, we assume in average 25–50 burials in one collective burial (Schiesberg, 2012), which led to the high numbers visible in Fig. 2.

Given the predominant practice of collective burials in our study area, the initial phase (Ph 2.1, 3300–2800 BCE) of the second instance of the pattern (P2, 3300–2200 BCE) proves difficult to capture with our proxy. In the time intervals from 3200 to 2800 BCE, we only observe 7 burial mounds in our data, which is the reason why we do not compute any inequality index. In phase Ph 2.1, there are mostly collective megalithic graves, but the types of monuments altered from dolmen variations to architectural elaborate passage or gallery graves. The latter ones show higher differentiation in size and labor investment. Also, fewer such monuments were built, and there was an increase in individual flat graves (Müller, 2019; Wunderlich et al., 2019; Wunderlich, 2019). This demonstrates the ability of some communities to acquire more relational wealth than their contemporaries and is similar to the first phase of our pattern. Ph 2.1 is associated with a resurgence of human activity observed in many regions around 3300–3000 BCE (Parkinson et al., 2021; Kolář et al., 2022). During this phase, two contemporary transregional trade networks of prestige goods played a major role in connecting major parts of our research area–jade axes in the Western region of our study area and copper tools in the Eastern region (Klassen, 2004; Pétrequin et al., 2012). In the subsistence economy cattle became important as draft animals as well as for dairy products (Weber et al., 2020; Evershed et al., 2022). In this respect, livestock may have acted as mobile capital.

The pattern (P2) continued into the second phase (Ph 2.2., 2800–2200 BCE). The shift from Ph 2.1 to Ph 2.2 is profound, as the building of collective burials was abandoned, and a single burial mound tradition became established (Brozio et al., 2019). In principle, the increase in the size of the upper societal segment could result from the low number of total burials. However, comparing the absolute number of burial mounds between 3800 and 2800 BCE and 2800 to 2200 BCE, the increase in the size of the upper societal segment seems reliable. The period from 2800 BCE onward is closely associated with the subcontinental cultural phenomenon of Corded Ware. The 3rd millennium BCE in Eastern and Central Europe is characterized by the creation of new and changing communication networks, including an influx of individuals from the Central Eurasian steppe (Furholt, 2021; Kristiansen et al., 2017; Papac et al., 2021). The level of inequality between the individuals of the upper societal segment is high but also changed during that period. An interesting observation is the significant decline in the Gini index in 2600–2400 BCE which cannot be directly linked to any major external event (e.g., climate, migration, disease). Nevertheless, the change could relate to the onset of the Bell Beaker phenomena in Central Europe from 2600 BCE onward (Heyd, 2007; Olalde et al., 2018) and a decline in population numbers beginning around 2500 BCE (Müller, 2013b). A further possible indicator for high social differentiation over the considered time frame is the establishment of clear gender differentiation from the beginning of the Final Neolithic (about 2800 BCE), which consolidated during the Bronze Age (Robb and Harris, 2018).

The pattern (P3) occurred a third time from 2200 to 1200 BCE, with its first phase (Ph 3.1) from 2200 to 1600 BCE. The Bond −4.2 ka climate event lasting from about 2350–1900 BCE—which is argued to have triggered the collapse of the Akkadian empire (Cookson et al., 2019; Bradley and Bakke, 2019)—did not have a uniform or strongly visible effect in our study area (Kleijne et al., 2020). With the later Early Bronze Age (2000–1600 BCE), tin bronze metallurgy became available in nearly all regions of our study area. However, access to metals, such as copper, tin, and gold, as well as other prestigious objects, was limited (Metzner-Nebelsick, 2021; Mittnik et al., 2019; Radivojević et al., 2019). Most of the burial mounds from 2000 to 1800 BCE belong to the so-called “princely” burials of the Únětice groups (2200–1600 BCE) in today’s Eastern Germany (e.g., Helmsdorf) and South-West Poland (e.g., Łeki Małe) showing high differentiation between each other. The size of the upper societal segment was small. The world-famous “Sky Disc of Nebra” as well as circular ditch enclosures connected to astronomical observation, hint at the control of knowledge (Meller, 2019). Differentiated house sizes in densely populated but not fortified settlements and fortification features at some settlements support the interpretation of a socially stronger differentiation on community and regional scale (Meller, 2019). The inequality between the individuals of the upper societal segment is substantially higher than in the previous periods. The overall increase of inequality from 2400–2200 BCE to 2000–1800 BCE is significant (p-value = 0.002). Moreover, the literature points to a growth in community sizes and population in general (Zimmermann, 2012). In addition to the increasing long-distance trade, which was dominated by the exchange of metals, the amber trade from the Baltic South shaped transregional networks in our research area (Ernée, 2016; Ling et al., 2013). Between 2000 and 1200 BCE, tin bronze became increasingly available, and improvements in bronze metallurgy emerged (Radivojević et al., 2019; Krause, 2003). These developments led to the establishment and increased use of bronze tools (e.g., sickles) or weapons (e.g., swords) from the Middle Bronze Age onward (Horn and Kristiansen, 2018; Arnoldussen and Steegstra, 2015). With the significant drop in inequality from 2000–1800 BCE to 1800–1600 BCE, the size of the upper societal segment grew larger as the increased number of burial mounds indicated.

The second phase (Ph 3.2, 1600–1200 BCE) started with a surge in burial mounds in our dataset that can be connected to the phenomenon of the so-called “Tumulus Culture” (ca. 1600–1300 BCE) and the early Older Nordic Bronze Age (ca. 1750–1500 BCE). This time frame is also characterized by major reorganizations in long-distance trade networks as well as economic and social changes often associated with the end of the Minoan society in the Mediterranean (Harding, 2000; Meller et al., 2013). Furthermore, from 1600 to 1200 BCE, the size of collectively acting groups shrunk, but we generally expect an increasing population size for this phase (Zimmermann, 2012; Müller, 2013b; Nikulka, 2016). Compared to the previous subphase (2200–1800 BCE), inequality between the individuals of the upper societal segment stayed constantly high throughout the period from 1800–1200 BCE but paused the general increasing trend for a while. An indicator of potential conflict at the end of Ph 3.2 is the battlefield of a possible caravan raid of Tollenseetal, Northern Germany, dating around 1300–1250 BCE, with possibly more than 2000 combatants involved (Lidke et al., 2017).

The final repetition of the pattern (P4) in our dataset has its first phase (Ph 4.1) from 1200 to 800 BCE and starts its second phase (Ph 4.2) around 800 BCE. At the beginning of 1200 BCE, millet was established and spread as a crop (Filipović et al., 2020). There was also an increasing usage of horses and chariots, but these seemed to be limited to the upper societal segment, which was of small size during this period (Metzner-Nebelsick, 2021; Jantzen et al., 2014). Based on the estimations of the size of collectively acting groups, the community became larger compared to preceding periods (Zimmermann, 2012; Nikulka, 2016). In addition, there was an increase in fortified settlements in the central and southern parts of our study area during 1200–800 BCE (Hansen, 2019). Inequality in relational wealth first increased compared to the previous interval and then again decreased to its former level. However, the decrease is statistically insignificant. The time frame from about 1200–800 BCE is also connected to the "Urnfield Culture", which is tied to the area-wide adoption of cremation as a dominating burial rite in Central and Northern Europe. It shared iconographic symbolism (Harding, 2000; Brunner et al., 2020; Falkenstein, 1997) and is argued to be influenced by major cultural changes in the Mediterranean (Knapp and Manning, 2016; Mühlenbruch, 2017).

The second phase (Ph 4.2) from 800–400 BCE, known as the Hallstatt Iron Age, is characterized by the introduction of iron as a "disruptive" force. It was scarce at the beginning of the period but later became increasingly available due to the exploitation of regional deposits (Kristiansen, 1998; Wells, 2011). Due to the considerable difference in sample sizes, the increase in inequality from 1000–800 BCE to 800–600 BCE is insignificant. Although the share of burial mounds increased, the strong social differentiation in the upper societal segment suggests the establishment of structural network positions that represent an institutionalized hierarchy. We expect local network importance for the individuals buried in smaller mounds, as the exceptionally high mounds represent pivotal positions in over-regional networks. The corresponding settlement system indicates a centralization process and the establishment of so-called "princely seats" or hilltop settlements in southern Central Europe. These settlements were often accompanied by large burial mounds of richly endowed individuals. The trade link to Mediterranean Greek colonies and the increasing use of the horse in combat and transportation also was an essential factor for social development (Wells, 2011; Krausse, 2010; Schumann and van der Vaart-Verschoof, 2017; Nakoinz, 2019). Emerging divisions of agricultural land, so-called "Celtic fields," appearing in the northern part of Central Europe hint at differentiated property rules (Arnold, 2011; Løvschal, 2014). The decline in inequality from 800–600 BCE to 600–400 BCE appears to be related to the collapse of some "princely seats," e.g., the Heuneburg, Germany, and Mont Lassois, France, during around 480 BCE. This transformation was followed by a sociopolitical reorganization and the beginning of the abandonment of hilltop settlements and the burial mound tradition in many parts of the southern parts of our study region (Fernández-Götz, 2017). Because of our temporal resolution, we miss a more precise picture of the development in the upper societal segment's inequality. The "princely seat" of the Heuneburg, for example, was established around 600 BCE and was abandoned in the mid-5th century BCE. During the occupation of the settlement, we expect similar high inequality as in the temporal block before. Moreover, the size of collectively acting groups peaked during the establishment of the princely seats and decreased after their disappearance (Zimmermann, 2012; Nikulka, 2016).

The time frame of our study concludes around 200 BC, limiting our ability to trace the continuation of the observed pattern into subsequent centuries. Notably, the Late Iron Age Hunsrück-Eifel regional groups (620–250 BCE) in the western part of our study area contribute to the rise in the Gini index and its very high level during the period 400–200 BCE. Around 300 BCE (possibly Ph 5.1), the establishment of large proto-urban centers known as "oppida" in the central and southern regions of our research area coincided with the emergence of an early monetary economy (Kristiansen, 1998). The conclusion of this phase could potentially be associated with the "Gallic Wars" and the Roman conquest in 58 BCE and 50 BCE (Wells, 2011).

Discussion

By using burial mound volume as a proxy for relational wealth, it is possible to broaden our view on different types of ancient inequality and include the network dimensions attached to it. We can show an increasing trend in inequality of relational wealth within an upper societal segment, likely connected to increasing overall population densities and advances in transportation and infrastructure. This trend, however, is not reflected in the share of the upper societal segment, which fluctuates over time, mostly initiated by external events. The differently scaled networks in our research area increased their connectivity; however, it seems that there were times when more people were involved in connecting the lower-scaled networks with each other and gained relational wealth.

The core findings of our investigation are in line with current research that suggests an evolution of social complexity, where especially increasing agricultural productivity, the introduction of technological innovations (e.g., metallurgy), and external conflicts seem to be related to the rise of state societies (Turchin et al., 2022). We link the general trend of increasing inequality at the top of society to technological and agricultural developments. Both variables influence small- and large-scale networks through their impact on density and connectivity via population growth and transport infrastructure. Moreover, our study also offers novel insights into ancient inequality, revealing the non-linear behavior of inequality in relational wealth and the shifting size of the upper societal segment over time. These findings highlight the significance of examining developments within distinguished societal segments in addition to studying inequality across the entire society to better understand ancient inequality.

Concerning access to networks, conflict and violence could be possible means in this regard. Indicators of violent conflict in our study area increase over time. The increasing presence of stone, bronze, and later iron offensive weapons such as axes, hatchets, swords, and spearheads in burials, but also the availability of metal defensive weapons and horse gear from the Late Bronze Age onwards, supports the establishment or at least the acceptance of violence as an identity marker (Horn and Kristiansen, 2018; Otto et al., 2006; Fernández-Götz and Roymans, 2017). Another indicator could be the gradual increase of fortified settlements over time (Hansen, 2019). However, it is too superficial to consider them only as signs of increasing violent conflict since they are also intra- and inter-communal social signals that testify to the power of their builders and are integral parts of regional and over-regional exchange networks (Veit, 2018; Brunner, 2023). The general idea that violence increases with the stratification of society to enforce the current social hierarchies should be brought into focus, as warfare or rebellion can be seen as a strategy to level the emerging social hierarchies and socio-economic asymmetric relations (Angelbeck and Gier, 2012). Conflicts in our study are less likely to be large external conquests but rather small-scale conflicts resulting from socio-political tensions or resource scarcity, perhaps rooted in larger-scale "disruptions" (Fernández-Götz, 2017).

Based on our findings, we hope to motivate future research in four aspects. First, there is a substantial gap in our knowledge about the development of inequality between individuals of specific societal segments. To better understand the historical and current trajectory of social inequality in general, the gap needs to be filled. Second, we have learned about the development of inequality in the upper societal segment and related it to changes in the sociopolitical structure of societies. But how peaceful were these changes? Did inter- or intra-group violence accompany them? Third, by focusing on inequality in relational wealth, we shed new light on a type of wealth that has been little studied. Thus, for future research, it seems interesting to us to explore different types of wealth in more depth and to provide quantitative evidence. Fourth, the spatial granularity of our dataset also enables regional analyses. To maintain a clear storyline, we have decided to leave these analyses for future research. We believe that integrating this data with other regional datasets can yield additional valuable insights into ancient inequality.

Data availability

The datasets generated and/or analyzed during the current study are available at https://doi.org/10.7910/DVN/IRB59T and upon request from the authors.

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Note

1 Other common measures of inequality used in empirical work are variance, coefficient of variation, relative mean deviation, and variance of logarithms (Atkinson, 1970). Although easy to compute, these measures are inferior to the Gini index and Generalized Entropy Measures. While the Gini is more sensitive to changes in the middle of the wealth distribution, the Generalized Entropy Measures can highlight inequalities in other parts of the distribution. Broader measures such as Sen's capability approach (Sen, 1985) are not applicable here because they require multidimensional data sets and are not yet sufficiently operationalized for statistical evaluation.

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