Journal of Archaeological Method and Theory
https://doi.org/10.1007/s10816-023-09625-6

RESEARCH

Linking Up Bell Beakers in the Iberian Peninsula

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Accepted: 27 September 2023

Abstract
Many studies in complexity theory employ agent-based models whose interactions can be expressed as networks. In such models, the pattern of interactions between actors is crucial, and the network topology that emerges from the raw data can be characterized through many metrics. One tool previously used in archaeology studies has the potential to deal with networks in social contexts at different scales of analysis: social network analysis (SNA). This discipline has been applied successfully in a wide range of archaeological problems, providing valuable insights and a different perspective. It also could be helpful to quantify concepts associated with social complexity, such as robustness or resilience. In this work, we propose some methodologic possibilities for consideration in the phase definition of the adaptive cycle model (ACM), using SNA tools. To illustrate the process, we will present a case study from the Copper Age in the Iberian Peninsula: the Bell Beaker phase.

Keywords Social network analysis · Bell Beaker · Copper Age · Adaptive cycle model · Iberian Peninsula

Introduction

Social complexity has been a subject of study in archaeology for a long time. The complex systems approach offers excellent potential to deal with social change and linkages between individual actors and society-level features. However, complex systems approaches have not yet coalesced into a homogeneous theoretical framework (Barton, 2014). From a general complex systems perspective, all human societies are complex systems, no matter how broad their structures are (Miller & Page, 2007; Mitchell, 2009). Human societies have been considered systems connected by flows of exchange, material, energy, and ideas, by many research traditions (Flannery, 1986; Moran, 1990; Rappaport, 1971). Complexity theory is

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Published online: 14 October 2023

a general theory made up of a related group of concepts and tools that focus on the effect of parts interacting on the system as a whole. From a broader perspective, complex systems are assemblages of interconnected agents that belong to the same system. Complex adaptive systems (CAS) are a class of these open systems. Human societies can also be characterized as CAS, and there are many examples of application in the field of archaeology (Bentley & Maschner, 2003; Bernabeu *et al*., 2012; Feinman, 2011). The components of CAS are organized in hierarchical groups that can be represented through the network science paradigm. It also includes some tools that may be of interest for formalizing complex systems in the form of networks. These include inference and the structural characterization of networks. This discipline assumes that its underlying structure contains information about its behavior which can be quantified through certain metrics (Bianconi, 2018). Of all the tools provided by network science, there is one that includes both the networks and the social perspective required for archaeological studies: social network analysis (SNA). This study aims to present a case study illustrating some new views for SNA in providing an approach to quantifying the phases proposed by the ACM in Resilience Theory (Holling and Gunderson, 2002). It will focus on the evolution of social complexity derived from networks of interaction, especially those shaped by the emerging local elites, during the Bell Beaker period in eastern Iberia. This period represents one of the most compelling examples of a cultural phenomenon associated with information circulation through social networks in late European prehistory. At the same time, it also poses many unanswered questions about its origins, spread, and further development (Lemercier, 2018), which will be addressed in this study.

Social Network Analysis

SNA methodology stands out from all the available tools used to quantify social phenomena across long diachronic series, due to its vast battery of metrics to measure them. The study of relational networks created in the past has recently been placed under the spotlight and has been the subject of growing interest among archaeologists (Knappett, 2011; Brughmans, 2013; Van den Berg, 2014; Collar *et al*., 2015). The implementation of a complex networks perspective in archaeological research has made significant breakthroughs possible in the knowledge of social dynamics from the Palaeolithic to the Middle Ages (Collar, 2007; Sindbæk, 2007; Coward, 2010; Brughmans *et al*., 2015; Gjesfjeld, 2015; Bernabeu *et al*., 2017b). Network methods have been successfully applied to various archaeological questions ranging from the spread of ideas to the movement of peoples and artifacts (Bernabeu *et al*., 2017a; Brughmans & Poblome, 2012; Knappett *et al*., 2008; Welsch & Terrell, 1998). Despite the different approaches, a common thread can be traced: all of them are focused on analyzing relationships between entities and the emergent patterns that can be recognized. These relationships are present in every single layer of human societies and exert their influence upon individuals, shaping the fabric in which information and artifacts flow. Network models typically consider the network structure and its impact on the agents in enabling or constraining individual action, or the transfer of resources (Wasserman & Faust, 1994). Many studies of social networks have focused on specifying the principles of exchange and power that apply to different network structures (Cook & Whitmeyer, 1992).

SNA has significant methodological flexibility and epistemological versatility, which enables quantitative and qualitative research. Its analytic techniques can be used to provide insights into many areas of archaeological inquiry related to social environments. Social networks can be analyzed based on individual-level attributes, whole networks, and subgroups within networks. Ontologically, SNA requires an emphasis on the connectivity and interdependence of individuals in a group. SNA can provide researchers with information that may improve our understanding of complex relationships and provide insights.

Furthermore, results may stand alone to answer a research question, or they can be incorporated as variables into statistical models. Both empirical and interpretive inquiry methods have successfully been used when incorporating complexity as a framework (Miller & Page, 2007).

The use of this perspective precludes considering individual entities or the structure separately (Brughmans, 2013), integrating collective behavior and individual agency in the same process (Bentley & Maschner, 2003). Complex networks became a handy tool in archaeology for studying variability in material culture through space and time. This variation is an emerging phenomenon that results from collective-individual interactions. As many studies point out (White, 2013), the material culture associated with archaeological contexts is directly related to the relational context in which they were produced. Connected individuals shape every human society; thus, these social ties constitute social networks, which are emergent phenomena produced by an individual's behavior. As people act as channels for information, they can be used to characterize a social system. However, this statement seems like a big jump; social networks articulate material culture well because technical learning is always placed in social contexts (Boyd & Richerson, 1988; O'Brien & Lyman, 2000; O'Brien & Shennan, 2010).

Moreover, it is essential to point out that social ties exert a great influence on information transmission. We can therefore state that the specific form of the material archaeological record is the subproduct of spatially located systems, information exchange, the communication of innovation, and social learning. Many studies also show that differences in the structure of the networks affect the behavior of real-world systems mediated by them, together with the patterns of material culture (Wobst, 1976). All of this therefore suggests that the structure of interaction may have an observable effect on the patterns of material record variability produced by cultural transmission processes (Bentley & Shennan, 2003; Bernabeu *et al.*, 2017a). This extended battery of metrics can greatly help quantify concepts associated with social complexity, which are very difficult to approach. It also has the potential to help resilience theory (Garmezy, 1985; Holling, 1973; Walker *et al.*, 2002) to characterize the different stages of the ACM (Bollig, 2016; Folke, 2006; Holling & Gunderson, 2002). Although most archaeological studies on resilience use this paradigm theoretically, some new ones demonstrate that it can be tackled from a mathematical perspective (Gronenborn *et al.*, 2014; Weinelt *et al.*, 2021). In this study, we will also propose some possibilities for approaching concepts associated with the ACM.

Geographic and Chronological Scope

The Bell Beaker phase signals a turning point in the dynamics associated with the Copper Age communities in the eastern Iberian Peninsula. It has been highlighted as the moment when social complexity and demographic growth increased and when social asymmetries started to become evident in the archaeological register; however, little evidence can be found in the material record that points to economic specializations which enable the merging of diverse social groups in complex systems of permanent decision-making structures. Some goods, such as Bell Beaker pottery, appear to be exchanged among a few individuals, suggesting the existence of a prestige-based mechanism channeled through rituals and a symbolic world, which would have been used for local ruling groups to form their relational framework (Garrido-Pena & Rojo-Guerra, 2014; Garrido-Pena, 1996).

As previous studies have pointed out (Bernabeu, 1984; Bernabeu & Martí, 1992; Juan-Cabanilles, 2005), there is little doubt about the clear image of continuity in the archaeological record throughout the fourth millennium cal BC and the first part of the third. Nevertheless, this homogeneity seems to fracture during the Bell Beaker phase. The interpretations provided for this cultural phenomenon are not homogeneous. Different approaches try to shed light on the dynamics of such a process by laying out alternative theoretical proposals based on World-systems Theory and Complex Systems, respectively (López-Padilla, 2006; Bernabeu *et al.,* 2006). The late Neolithic culminates a long period that crystallizes in the fourth millennium BC with increasing social complexity that will lead to the Copper Age. As not all the burials in this period contain Bell Beaker grave goods, we can assume that raw materials and prestige objects circulated among the emerging ruling cliques (Juan-Cabanilles, 2005). This process culminated in the Bell Beaker phenomenon, which signaled an inflection point in the background of the third millennium BC.

The geographic framework comprises the eastern and southeastern Iberian Peninsula (Fig. 1). Archaeological excavations in the area made it one of the best-known in Spain for studying the Copper Age (Bernabeu, 1993; Bernabeu *et al.*, 2018; Molina *et al.*, 2004; Garrido-Pena, 1996; López-Padilla, 2006). The study area is defined by the basins of the Almanzora-Andárax Rivers in the south and the Ebro River in the north. It contains a wide variety of landscapes encompassed by the coastal platform and the ridges of the Iberian and Prebaetic Systems. They shape a terrain characterized by mountainous areas and flat coastal plains connected by valleys that work as natural corridors (Aura-Tortosa *et al.*, 1993).

As the scope of this study is focused on the Bell Beaker phase, the timeframe will be established by the available radiocarbon determinations, all between 2500 and 2050 cal BC. All the evidence shows that from the middle of the fourth millennium cal BC, social groups began to present specific signs of inequality probably deriving from an extensive agricultural model (Pérez-Jordà *et al.*, 2021). In addition, studies of the fauna point to an increase in cattle and the exploitation of associated products

Fig. 1 Decorated Bell Beaker site distribution

such as milk and derivatives (Pérez-Ripoll, 1999). Furthermore, during the Copper Age, the intensity and number of exchange networks increased considerably, especially in the southeastern region (López-Padilla, 2006; Pascual-Benito, 1998). These networks seem to include the transmission of artifacts and the techniques associated with their crafting, and raw materials such as copper (Rovira & Montero, 1994). Evidence from sites such as La Vital (Gandia) (Pérez-Jordá *et al.*, 2011) suggests that copper was imported as a raw material and was processed at the site. Therefore, we can support the existence of a metallurgical horizon before the Bell Beaker phase.

Recent works (Bernabeu *et al.*, 2018) have also highlighted the extraordinary demographic growth occurring at the end of the Neolithic in the Mediterranean region of the Iberian Peninsula, following a settlement pattern in the bottoms of valleys close to watercourses, in which there is a significant correlation between storage pits and habitational spaces (Bernabeu & Orozco, 2014; Jiménez-Puerto *et al.*, 2018). Furthermore, some domestic structures could potentially contain far more resources than were needed (Bernabeu *et al.*, 2006). All of this suggests that part of the surplus production was being hoarded by some community groups, which on the other hand were unable to consolidate their primacy. In addition, we cannot overlook the transformation of ritual and grave goods associated with some burials, evidencing the differentiated consumption capabilities of some segments of the social groups (Oreto García-Puchol *et al.*, 2013).

The material record of the communities on the Mediterranean coast, from Almería in the south to the Júcar River in the north, is very homogeneous, and many similarities can be observed (López-Padilla, 2006; Pascual-Benito, 1998). It therefore follows that these social groups could have been part of a more comprehensive relational network in which ideas and objects circulated (Furholt, 2020). Bell Beaker pottery is abundant in the Mediterranean region of the Iberian Peninsula. The so-called international styles shape the first Bell Beaker pottery horizon. From that moment on, an inflection point can be observed in sites such as Los Millares (Almería), beginning a period when large settlements broke up and were replaced by smaller aggregated habitats (Molina *et al*., 2004, 2020). This process, evident at the sites and burials from the same period in Alicante and Valencia, has traditionally been associated with the social disintegration that occurred just before the appearance of the Argaric culture (Jover-Maestre & García-Atienzar, 2014; Lull *et al*., 2010). During the Bell Beaker period, the predominant funerary ritual in natural cavities continued, but the number of bodies buried fell dramatically, and greater numbers of weapons and exotic raw materials (*i.e*., barbed and tanged flint arrowheads, copper knives, ivory) are recorded as grave goods. The late part of the Bell Beaker phase has traditionally been associated with a period of crisis, increasing the potential for conflict and cultural fragmentation (López-Padilla, 2006; Lull *et al*., 2013). It also appears to be a moment that witnessed the contraction of interaction networks, which tend to be limited to increasingly local connections (Lillios *et al*., 2016). Recently, diffusionist theories have become popular thanks to genetic analyses that point to the arrival of new gene pools in the peninsula (Olalde *et al*., 2019), although their conclusions are controversial. Furthermore, as many studies have pointed out (Bini *et al*., 2019; Blanco-González *et al*., 2018; Hinz *et al*., 2019), environmental changes must be taken into account as well. This is the case of the paleo-environmental studies highlighting a wide range of climatic events around 4.2 ka.

Nevertheless, the research has come up against significant limitations due to the scarcity of a closed archaeological context for the Bell Beaker phase. Many of these arise from altered environments or earlier excavations with little stratigraphic information (Bernabeu, 1984; Garrido-Pena, 1996; Juan-Cabanilles, 2005) and a considerable absence of short-lived radiocarbon determinations (Ríos *et al*., 2011). Another difficulty is associated with the calibration curve and the high error margins associated with this period. Defining a chronological framework is therefore a very challenging task.

Be that as it may, despite the growing complexity in the relational sphere, during the third millennium BC, there is little evidence of the existence of economic specialization and interdependencies with the potential to merge diverse social groups into permanent decision-making structures. Some of the items which circulated among a few individuals suggest the validity of mechanisms such as the prestige and the exclusive ideology of the elites, which are probably responsible for the network's development and would be a key variable in the process of increasing complexity that reached its peak at the end of the Bell Beaker phase. It is necessary to make it clear that this only holds true in comparison with the subsequent Bronze Age, but this aspect falls outside of the scope of this study.

Materials and Methods

This study focuses on the Bell Beaker phase and addresses the idea of connectivity through a methodology that is increasingly popular in archaeology: Social Network Analysis (SNA). Previous studies have addressed this issue using a network perspective (Caraglio, 2020; Caraglio *et al*., 2022; Clarke, 1976; Kleijne, 2019). The ceramic wares associated with the Bell Beaker phenomenon are a marker for a new symbolic world associated with the emerging elites (García-Puchol *et al*., 2013; Garrido-Pena & Rojo-Guerra, 2014; Garrido-Pena & López-Astilleros, 2000; Lemercier, 2011; Salanova, 2005). The networks needed to perform the analysis will be based on similarity. The variables used to quantify the similarities are defined with stylistic and morpho-technical criteria applied to decorated ceramic wares, creating ad hoc styles. Moreover, a Bayesian classification procedure will be used to provide a chronological framework. These tools together will make it possible to use a relational approach that enables the connection of archaeological information from a wide range of contexts in a large area, and a diachronic axis, following the flow presented in Fig. 2.

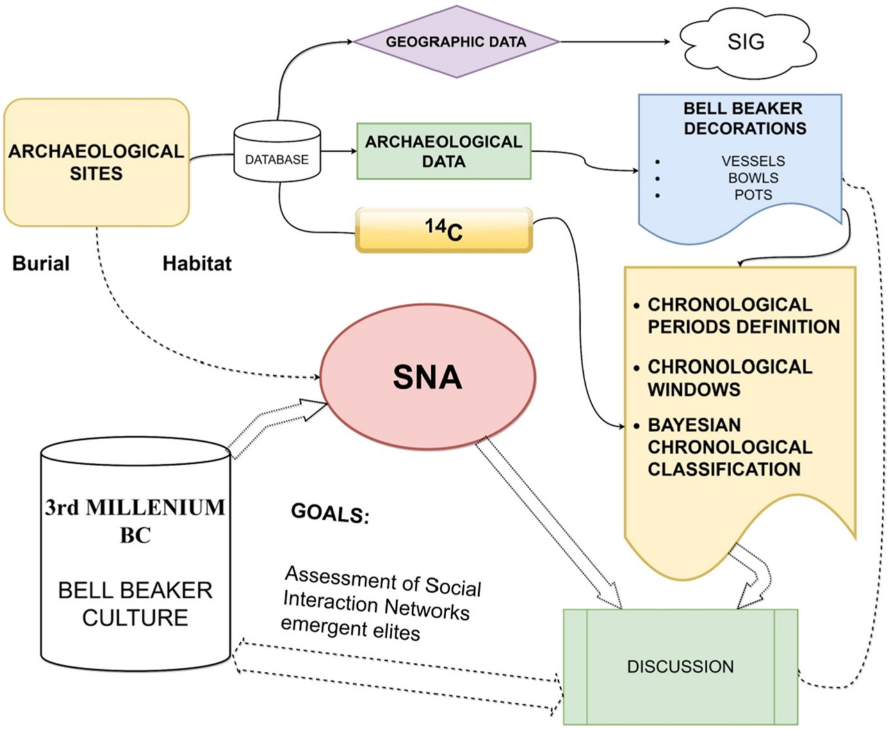


Fig. 2 Procedure flow chart

Bell Beaker Decorations

There is a long tradition of studying the pottery in this area. Many methodological tools have been developed to analyze every formal aspect (Bernabeu *et al.*, 2011, 2017b; Fenyvesi & Lähdesmäki, 2017). The organization of decorations and their relation with symbolic beliefs has been emphasized by many studies (Cunningham, 1973; Washburn *et al.*, 2010; Wilbert, 1993). Bell beaker wares are closely associated with a change in the symbolic world of the emergent Copper Age elites (Bernabeu, 1984; García-Puchol *et al.,* 2013). One of the most remarkable aspects of the Bell Beaker phase is related to its presence in burials, which do not represent all of the community due to the low numbers of associated individuals. That means only a tiny proportion of the group were given such symbolic treatment. The rest were buried in other ways, as evidenced in the Madrid region's much-studied sites (Liesau & Blasco, 2011; Garrido-Pena *et al.*, 2019). The materialization of Bell Beaker pottery in the study area is diverse, and its coexistence with previous funerary practices is evident in many places (Pascual *et al.*, 2005). Together with the decorated vessels, artifacts associated with warfare (copper knives, Palmela arrowheads) can be found. These grave goods are usually related to individuals whose power would be supported by an ideology in which the display of power would be socially appreciated (Salanova, 2005; Lemercier, 2011). This new symbolic paradigm and the decorated ceramic wares are associated with ceremonials in which alcoholic beverages were consumed (Sherrat, 1987; Rojo-Guerra *et al.*, 2008), possibly connecting the world of the living and the dead. The analysis of the information flows that played their part in the spread of Bell Beaker pottery could be extremely helpful when considering the question of the symbolic transformation of Copper Age ruling groups.

Bell Beaker vessels were produced locally, as other studies have pointed out (Barroso *et al.*, 2015; Blasco *et al.*, 2011; García-Puchol *et al.*, 2014); the decorations, however, are highly standardized, primarily the corded and herringbone wares, which are supposed to be the oldest. Nevertheless, stylistic variability is greater among the later ones (incised and incised-stamped), leading us to picture a scenario with different regional groups. This suggests that the transmission of information between the communities was more homogeneous in the first part of the Bell Beaker phase, connecting vast geographic regions. This situation, however, breaks down in the latter part, resulting in a fragmented panorama. This circumstance makes decoration a pivotal aspect for analyzing the transmission/diffusion of information at a macro scale.

The decorative patterns of Bell Beaker pottery present some problems. Chronological attribution of the main decorative styles is one of them (Bailly & Salanova, 1999; Salanova, 2005). Despite the spectacular findings at many sites with radiocarbon determinations on short-lived samples (Humanejos, Camino de las Yeseras, Túmulo de la Sima or La Vital), the mixture of vessels decorated in different styles in the same context makes it difficult to get a clear idea. The difficulties associated with the calibration curve must also be mentioned. The existence of a long distribution plateau for this period introduces a significant factor of uncertainty in the equation. In addition, the interpretation of the Bell Beaker phase is far from complete. The ceramic wares are the visible part of a wide range of events framed in the context of migrations, the circulation of artifacts, and the transmission of ideas. The origins of this phenomenon, its accurate dating, and the axis of its diffusion are yet to be determined. Moreover, there are also many questions about its impact on the regional development of the earlier late Neolithic cultural groups (Lemercier, 2002). Finally, another question must be answered concerning the late Bell Beaker period and the transition to the Bronze Age.

The sample comprises exclusively Bell Beaker decorated ceramics. The sample (Jiménez-Puerto & Bernabeu, 2023) is a subset of a larger open-access database (Jiménez-Puerto, 2022b), and it contains information from 99 archaeological contexts. The Bell Beaker vessels included were all complete enough to consider the techniques used to decorate them. Small fragments and those that did not provide suitable information were ruled out. As the Jaccard index has been calculated, the final information was limited to the presence-absence of the studied decorative types in each archaeological level. The sample has been organized by considering the following criteria. The first layer of the classification uses functional and morphologic criteria. It separates the sample into two categories, vessels and bowls-pots, but only those that allow an almost complete reconstruction of the decoration have been considered. These two groups were formed because they seem to appear in the archaeological record for different reasons. On one hand, the vessels are found mainly in funerary contexts and seem to appear earlier.

On the other hand, bowls and pots appear later, found in both habitat and burial contexts. In addition, so-called International decorations are absent from bowls and pots, which tend to present late-fashion compositions. The second layer of the classification focuses on the techniques used to decorate the pottery (Fig. 3). The main techniques are as follows:

- **Corded**: composed of horizontal lines made from cord stamps.
- **Stamped**: a stamp made with a gradine. Decorative patterns are usually formed of horizontal motifs, but there are many variants.
- **Stamped short-lined**: a stamp shaped like a short stroke. It is performed with a tool with a short edge. It is always found in combination with other techniques, like incised.
- **Stamped polygon shaped**: it is defined by the use of a tool with a polygonal edge to make the stamps. It is always found in combination with other styles. It is widespread in the regional styles, characteristic of the late Bell Beaker period.
- **Incised**: Incision made with a pointed tool.
- **Ungulated**: a pinch made with the fingertips. It is rare but is always found with other Bell Beaker wares associated with the early phases, and it has probably gone unnoticed in many assemblages.

It is essential to mention that these techniques can also be found combined. Not all the associations of techniques are present, though. Some categories have been constructed, grouping all the possible combinations together in the two main forms, vessels and bowls-pots (Table 1). Additionally, some of them have a clear chronologic value. That is the case of E1 and E2, which are found mainly in regional styles such as Ciempozuelos, traditionally associated with late Bell Beaker contexts.

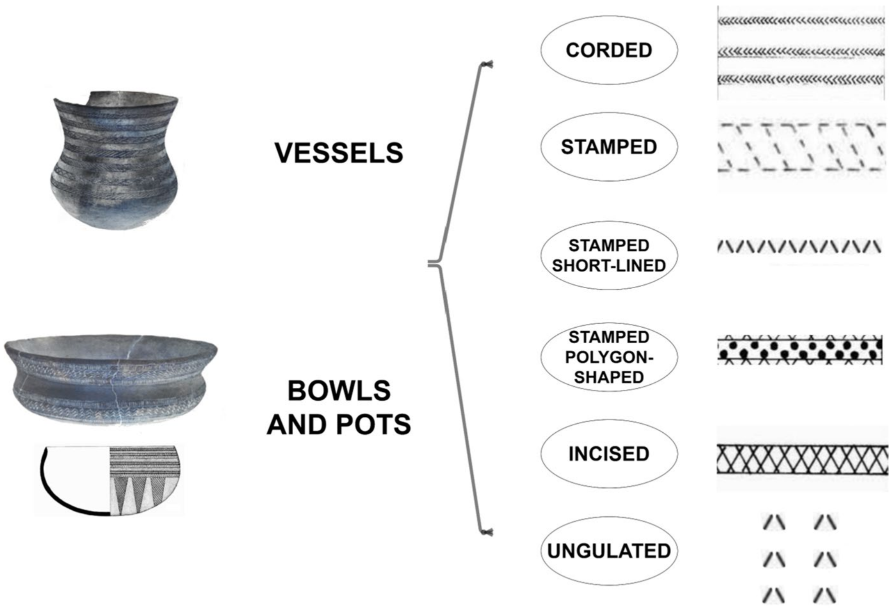


Fig. 3 Main individual techniques that can be found in the decorations

Table 1 The most commonly combined techniques are associated with the main shapes

Bell Beaker vessels	
B1	1A. Corded and Gradine + corded
	1B. Gradine
	1C. Gradine together with any other technique but corded
D1	1D Incised
E1	1E. Incised + Stamped Short-lined
	1F. Incised + Stamped Polygon-Shaped
Bowls and pots	
B2	2B. Gradine together with any other technique but corded
D2	2C. Incised
E2	2D. Incised + Stamped Short-lined
	2E. Incised + Stamped Polygon-Shaped

Bell Beaker Techniques Phase Modeling

As previously stated, the chronology of Bell Beaker wares is problematic and presents a series of issues as yet unresolved. To make the temporal framework as accurate as possible, we propose a chronological phase model with the Bayesian chronological modeling tool Chronomodel (Lanos & Philippe, 2018). It will enable us to create a framework in which to carry out the chronological attribution of the archaeological contexts dealt with in this study. As an organizational basis for the model, we have used the technical categories previously commented on, and the available ^{14}C short-lived determinations for the study area have been used. We have made sure all of them come from closed contexts and short-lived samples to minimize the uncertainty; however, it is necessary to add some determinations from areas that are not included in the study to ensure that some techniques are represented properly (Table 2).

Many combinations have been tried, and finally the most statistically robust one includes three successive periods. These periods have been defined by the stylistic and stratigraphic criteria suggested by the academic literature (Harrison, 1977; Bernabeu, 1984; Garrido-Pena, 2000; Rojo-Guerra *et al.*, 2005). It is essential to mention that the techniques are usually found combined, so the most common combinations have been taken to define the periods. The only technique excluded from the model is corded ware because it lacks ^{14}C short-lived determinations. It has however been associated with early Bell Beaker periods according to stratigraphic criteria (Suarez-Otero, 1996). The model proposes phase delimitations that can be followed in Fig. 4. As can be seen, the two horizons (first and third periods) do not overlap and are easy to distinguish. That is not the case in the second period, which overlaps with both the first and the third, acting as a transitional phase, which is sometimes difficult to detect. The first period corresponds to the stamped techniques traditionally associated with the so-called international styles, corded, gradine-corded, and ungulated. They are followed by a combination of stamped plus incised-stamped wares. Finally, the late productions are characterized by combinations of incised-stamped decorations.

The resulting model is consistent with the findings provided by stratigraphy and will be used to perform the Bayesian Chronological attribution of all the contexts with no ^{14}C determination, as discussed in the next chapter. It should also be noted that period 2 overlaps with periods 1 and 3, which are the ones that represent chronologically distinct moments.

Bayesian Attribution

All the archaeological contexts with information from artifacts but no absolute chronology have been processed using a novel procedure that has been tested and published recently (Pardo-Gordó *et al.*, 2022). This procedure associates any archaeological level with a previously defined period. We used our chronological phase model to represent our periods or windows (Fig. 4). Each period will be characterized through the artifacts in contexts with absolute short-lived radiocarbon determination, confirming the so-called *a priori* (Table 3). The automatic Bayesian method is based on the Dirichlet-multinomial inferential process (Alvares *et al.*, 2018), which uses the *a priori* information to predict the periods associated with a particular artifact assemblage.

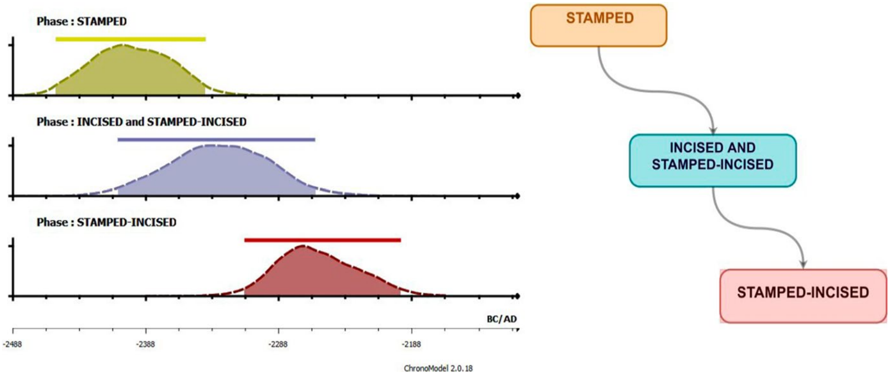
Once the periods are characterized, the multinomial classifier proposes a graph for each level in which we can find an estimation of probability for each window. Although there are clear situations, it is necessary to define a threshold value for all those that are not, together with some rules to apply when uncertain. In this case,

Table 2 ^{14}C determinations were used for the Bayesian modeling

Site	Locality	Province	Level	ID	Date	SD	Species	Phase	Bibliography
Majaladares II	Borja	Zaragoza	Cave	UBA31949	3721	40	Fauna	INCISED-STAMPED	Aguilera 2022
Majaladares II	Borja	Zaragoza	Cave	UBA31950	3766	37	Fauna	INCISED-STAMPED	Aguilera 2022
La Vital	Gandia	Valencia	Group 10	Beta229791	3920	50	Human	STAMPED	Pérez-Jordá *et al*. 2011
La Vital	Gandia	Valencia	Group 11	Beta222443	3830	40	Human	STAMPED	Pérez Jordá *et al*. 2011
Camino de las Yeseras	San Fernando de Henares	Madrid	Small cave 2 II	Beta184837	3740	40	Human	INCISED-STAMPED	Blasco *et al*. (2007)
Fuente Olmedo	Fuente Olmedo	Valladolid	Tumulus	CSIC483	3620	50	Human	INCISED-STAMPED	Delibes, Guerra y Tresserras 2009
Fuente Olmedo	Fuente Olmedo	Valladolid	Tumulus	OxA2907	3730	65	Human	INCISED-STAMPED	Delibes, Guerra y Tresserras 2009
Humanejos	Parla	Madrid	Grave 2	GrM15295	3945	25	Human	STAMPED	Ríos Mendoza 2011
Humanejos	Parla	Madrid	Grave 4	CNA4025	3918	33	Human	STAMPED	Ríos Mendoza 2011
Humanejos	Parla	Madrid	Grave 4	GrM15288	3925	25	Human	STAMPED	Ríos Mendoza 2011
Humanejos	Parla	Madrid	Grave 5	CNA4023	3941	33	Human	STAMPED	Ríos Mendoza 2011
Humanejos	Parla	Madrid	Grave 5	GrM15291	3910	25	Human	STAMPED	Ríos Mendoza 2011
Humanejos	Parla	Madrid	Grave 1	GrM16341	3820	45	Human	STAMPED + INCISED-STAMPED	Ríos Mendoza 2011
Humanejos	Parla	Madrid	Grave 1	Ua43524	3917	33	Human	STAMPED + INCISED-STAMPED	Ríos Mendoza 2011
Humanejos	Parla	Madrid	Grave 1	Ua43525	3797	32	Human	STAMPED + INCISED-STAMPED	Ríos Mendoza 2011
Humanejos	Parla	Madrid	Grave 7	Ua40217	3781	36	Human	STAMPED + INCISED-STAMPED	Ríos Mendoza 2011
Humanejos	Parla	Madrid	Grave 7	Ua40218	3825	37	Human	STAMPED + INCISED-STAMPED	Ríos Mendoza 2011
Humanejos	Parla	Madrid	Grave 9	GrM15296	3920	25	Human	STAMPED + INCISED-STAMPED	Ríos Mendoza 2011

Table 2 (continued)

Site	Locality	Province	Level	ID	Date	SD	Species	Phase	Bibliography
Humanejos	Parla	Madrid	Grave 9	Ua41491	3679	35	Human	STAMPED + INCISED-STAMPED	Ríos Mendoza 2011
Humanejos	Parla	Madrid	Grave 3	GrM15426	3895	20	Human	INCISED-STAMPED	Ríos Mendoza 2011
Humanejos	Parla	Madrid	Grave 3	Ua423526	3875	31	Human	INCISED-STAMPED	Ríos Mendoza 2011
Humanejos	Parla	Madrid	Grave 6	GrM15289	3905	20	Human	INCISED-STAMPED	Ríos Mendoza 2011
Tumulo de la Sima	Miño de Medinaceli	Soria	3	KIA17999	3860	30	Human	STAMPED	Rojo *et al*. 2005
Tumulo de la Sima	Miño de Medinaceli	Soria	3	KIA18000	3862	28	Human	STAMPED	Rojo *et al*. 2005
Valle de las Higueras	Huecas	Toledo	Cave 1	Beta145275	3890	40	Human	INCISED-STAMPED	Bueno Ramírez *et al*. (2005)
Valle de las Higueras	Huecas	Toledo	Cave 3b	Beta157732	3830	40	Human	INCISED-STAMPED	Bueno Ramírez *et al*. (2005)
Valle de las Higueras	Huecas	Toledo	Cave 5	Beta157729	3790	40	Human	INCISED-STAMPED	Bueno Ramírez *et al*. (2005)
Mola d'Agres	Agres	Alacant	Pit	Beta286988	3790	40	Seed	INCISED-STAMPED	García Atiénzar (2016)
Peñon de la Zorra	Villena	Alacant	Phase 1	Beta332584	3900	40	Seed	INCISED-STAMPED	García-Atiénzar (2016)
Peñon de la Zorra	Villena	Alacant	Phase 1	Beta445745	3870	30	Seed	INCISED-STAMPED	García-Atiénzar (2016)
Quintaret	Montesa	Valencia	Q138	Beta348075	4010	30	Seed	INCISED-STAMPED	García-Puchol *et al*. 2014



	START	END
PERIOD 1 (STAMPED)	-2455 cal BC	-2334 cal BC
PERIOD 2 (STAMPED & INCISED-STAMPED)	-2408 cal BC	-2261 cal BC
PERIOD 3 (INCISED-STAMPED)	-2313 cal BC	-2197 cal BC

Fig. 4 Model definition and results with Chronomodel (Philippe Lanos *et al*., 2016)

we have set a threshold of 0.25 to accept a prediction (Fig. 5-A), rejecting those not reaching it (C). The threshold value selection follows no specific statistical criterion and we have followed the recommendations of the creators of the method (Pardo-Gordó *et al*., 2022). When the results are not conclusive, they are compared with the information provided by stratigraphy and the associated material record, which was extracted from the available excavation reports, publications and monographic articles. In most of the cases the procedure was satisfactory, but there were a few cases in which there was no clear attribution, such as the bimodal distributions. All the bimodal distributions have finally been discarded (D). Also, when a period reaches 0.75, all the others are ruled out regardless of their probability (B).

Networks

Once each context has its chronological attribution, the next step is the composition of the similarity networks that are used to perform the SNA. It is necessary to convert the archaeological into relational matrices. The similarity coefficient used to conduct that study is the Jaccard (Jaccard, 1912; Liu *et al.,* 2016) as it does not take into account the absolute frequencies in the calculation, but it does the presence-absence of each item, in order to avoid biases produced by collections with many items (Jiménez-Puerto, 2018). The Jaccard coefficient also needs to be normalized to compensate for the variability between the chronological windows with few variables present, so we have used the formula proposed in previous studies (Bernabeu *et al*., 2017a). Another issue that must be addressed is that similarity networks tend to present high link densities because any similarity between two nodes generates a link between them, no matter how small it is, something that usually introduces noise in the subsequent analyses. A usual practice to avoid this problem is to

Table 3 Dated archaeological contexts confirm the *a priori*, together with their artifact content

Id	Site	Locality	Level	Province	1A	1B	1C	1D	1E	1U	2B	2C	2D	2E	Period
Huecas02	Valle de las Higueras	Huecas	Cave 1	Toledo	0	0	0	0	0	0	0	0	2	0	**3**
Huecas07	Valle de las Higueras	Huecas	Cave 3b	Toledo	0	0	0	0	0	0	0	0	1	0	**3**
Huecas11	Valle de las Higueras	Huecas	Cave 5	Toledo	0	0	0	0	1	0	0	0	1	2	**3**
Humanejos16	Humanejos	Parla	Grave 6	Madrid	0	0	0	0	1	0	0	0	0	0	**3**
Maja03	Majaladares II	Borja	III	Zaragoza	0	0	0	0	0	0	0	0	0	3	**3**
Olmedo03	Perro Alto	Fuente Olmedo	-	Valladolid	0	0	0	0	1	0	0	0	0	2	**3**
Yeseras12	Camino de las Yeseras	San Fernando de Henares	Small cave 2 II	Madrid	0	0	0	0	1	0	0	0	1	1	**3**
Zorra54	Peñón de la Zorra	Villena	Phase 1	Alacant	0	0	0	0	1	0	0	0	4	7	**3**
Humanejos08	Humanejos	Parla	Grave 3	Madrid	0	0	0	0	0	0	0	0	2	0	**1**
Humanejos10	Humanejos	Parla	Grave 4	Madrid	0	0	1	0	0	0	1	0	0	0	**1**
Humanejos15	Humanejos	Parla	Grave 5	Madrid	0	3	0	0	0	1	1	0	0	0	**1**
Humanejos29	Humanejos	Parla	Grave 2	Madrid	0	1	0	0	0	0	0	0	0	0	**1**
Medinaceli03	Túmulo de la Sima	Miño de Medinaceli	3	Soria	0	2	0	1	0	0	0	0	0	0	**1**
Vital02	La Vital	Gandía	Group 11	Valencia	1	0	0	0	0	0	0	0	0	0	**1**
Vital311	La Vital	Gandía	Group 10	Valencia	0	1	0	0	0	0	0	0	0	0	**1**
Humanejos06	Humanejos	Parla	Grave 1	Madrid	0	0	0	0	2	0	1	0	1	2	**2**
Humanejos22	Humanejos	Parla	Grave 7	Madrid	0	2	0	0	1	0	0	0	3	0	**2**
Humanejos27	Humanejos	Parla	Grave 9	Madrid	0	1	0	0	1	0	1	0	0	0	**2**

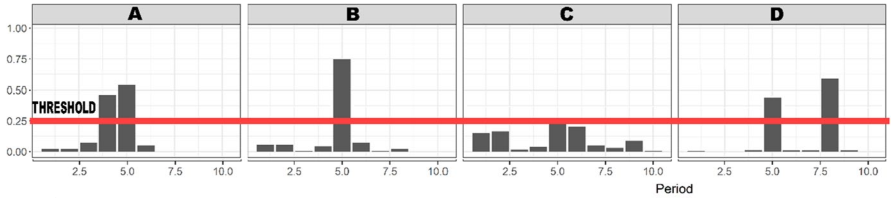


Fig. 5 Different situations processed by the multinomial classifier. This image comes from a random example with ten periods involved, to make the situations clearer

apply mechanisms such as thresholds. In this study a threshold of 0.25 was used. Finally, the networks have been arranged according to their geographical situation, using the Gephi application (Bastian *et al.*, 2009; Jacomy, 2011). Once composed of the networks corresponding to each window, some metrics have been analyzed to determine the diachronic evolution. In this network application, we have applied some available metrics and tools to trace diachronic development through the different windows. We have focused on the betweenness centrality measure, which provides an idea of the role played by each actor in the information flow, allowing us to detect bottlenecks. It has the potential to help in the characterization of the network's topology, enabling the detection of situations in which the structure is sensitive to perturbations in the information flow (Barthelemy, 2004) or potential edge-of-chaos situations (Kanders *et al.*, 2017; Langton, 1990), which compromise the robustness of the network. Robustness is the ability to withstand failures and perturbations and is a critical attribute of complex networks (Qin *et al.*, 2013). If robustness is low, the network flow has a higher risk of collapse. The breakdown of a complex network happens abruptly during a phase transition at some critical fraction of nodes removed (Cohen *et al.*, 2000), and its threshold changes from one topology to another. For example, scale-free distributions are resilient to attacks that knock out nodes randomly but are vulnerable to targeted attacks on the hubs. We have done a robustness test for all three periods to clarify this point. Finally, we have implemented some different community detection analyses to contrast the results: Girvan-Newman (Despalatović *et al.*, 2014; Girvan & Newman, 2002) and statistical inference (Zhang & Peixoto, 2020). The nature of large, interconnected networks makes it practically impossible to detect the underlying communities manually. Although these networks are not big enough to make inspection impossible, the methods enable the intersubjective reproducibility of the results. In this context, community detection algorithms are used to find groups of densely connected components inside the network, which share a common background.

Results

The network graphs composed taking into account the techniques associated with the decorations (Table 1) allow us to observe the changes in the distribution of the main shapes-techniques. Although Bell Beaker pottery reached the Iberian

Peninsula circa 2550 cal BC, its presence is not confirmed until 2500 cal BC. The decorated wares corresponding to Bell Beaker international styles can be found around the studied area in the first period. Each node represents a context belonging to an archaeological site. All of them have been arranged according to their geographic location using the Gephi plugin Geolayout (Jacomy, 2011), so the networks contain a geographic component. (Figs. 6–9). The color of each node represents its degree. Light shades indicate a lower number than dark ones. The size signifies the betweenness centrality of each node: the bigger the node, the more significant the value. The intensity of the link between two nodes indicates the weight; the more intense, the heavier.

We have assumed that all the sites present at a specific window are contemporaneous. However, this may not always be the case. As discussed in the conclusions, the definition of the available radiocarbon series placed a limitation on this study, something that will need to be addressed in future studies. Furthermore, the chronologic overlapping of the second and first periods must be discussed. The low chronologic definition of period 2 seems to be related mainly to its characterization, which comes from only one site (Humanejos). The results, however, are consistent with the material culture associated with the period. These correspondences remind us that the second period acts as a transition between the early Bell Beaker period and its homogeneous styles and the late period with the heterogeneous regional types (Bernabeu, 1984; Juan-Cabanilles, 2005). The nearly equal duration provided by the chronological model for the first and third periods reinforces this impression. The SNA is focused on some metrics, such as density, clustering, and average path

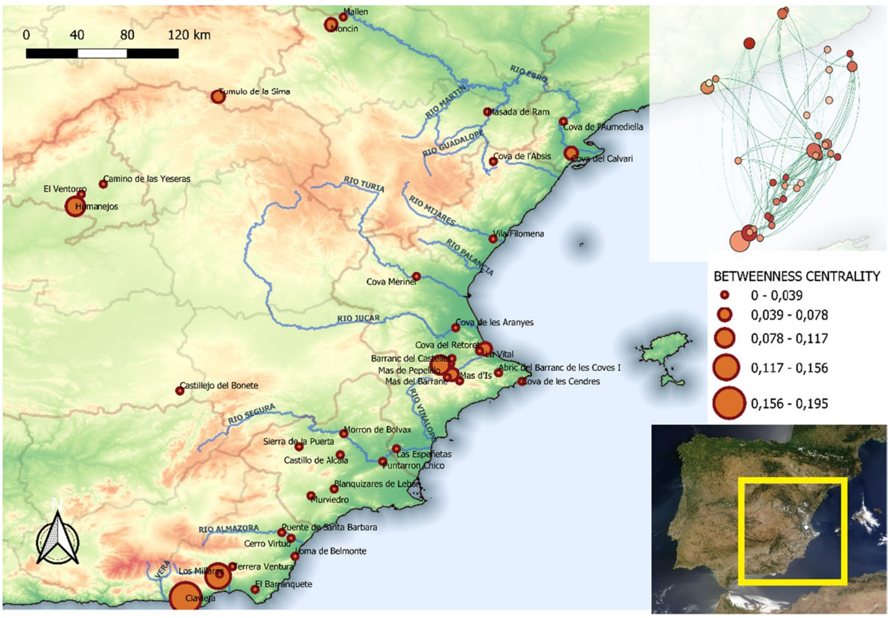


Fig. 6 Graph visualization of the networks corresponding to the nodes of the first period. The size indicates the betweenness centrality. The small window on the right shows the links

length, as shown in Table 4. Interestingly, density values increase monotonically throughout the period, despite the strong variations in network size.

The first period (c. 2450-2340 cal BC) (Fig. 6) clearly shows a connected world. The external nodes present higher betweenness values, together with the Serpis Valley region. Note that a high betweenness value can point to a central node or an actor that plays a frontier role in the network (Barthelemy, 2004). This suggests a world in which the different clusters are well connected. The central and southern coastal regions (south of the Júcar River) are densely connected, and sites such as Los Millares-Ciavieja play a significant betweenness role. Additionally, a not-so-dense cluster can be found to the north of the Turia River that reaches the mouth of the Ebro River. Furthermore, the central valleys (Júcar, Ebro, Turia) and Almansa corridor connect the littoral with the Meseta and Tajo basins. However, the links show lesser intensity than those connecting the coastal regions.

The second period (c. 2408-2261 cal BC) (Fig. 7) acts as a pivot and shows symptoms of disintegration. Generally speaking, the intensity of contacts is reduced in all areas. Nevertheless, the area south of the Júcar River maintains its inner connectivity, and the Los Millares site still plays a significant betweenness role. The regions to the north, especially the Ebro basin, seem to cease exerting their influence on the southern sphere, although they maintain a slight connection with the central area.

In the third period (c. 2313-2197 cal BC) (Fig. 8), the southeastern sphere loses much of its influence over the network. On the contrary, the connections between the central coastal area, the Tajo headwaters, and the Iberian System mountains increase dramatically, now playing an increased betweenness role. In general, most nodes'

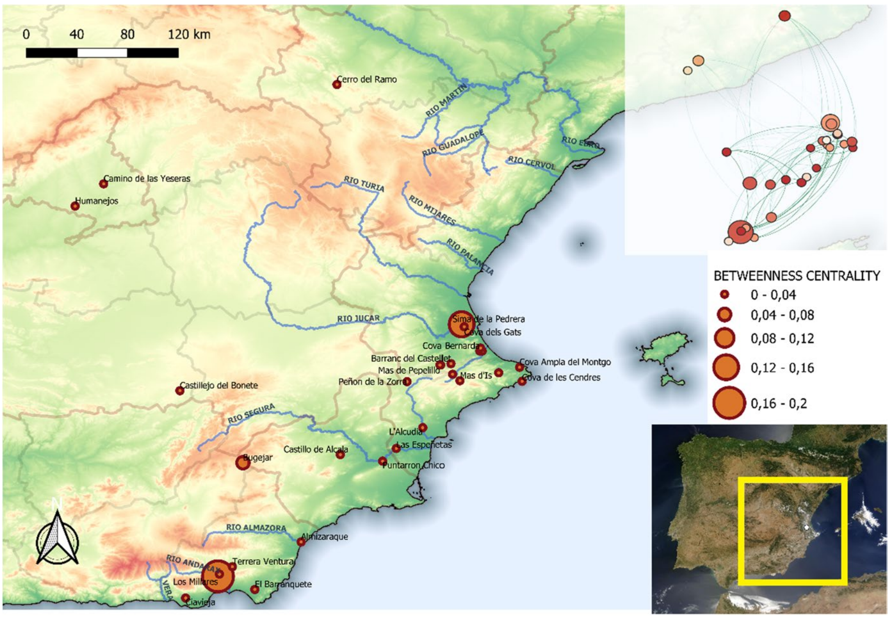


Fig. 7 Graph visualization of the networks corresponding to the nodes of the second period. The size indicates the betweenness centrality. The small window on the right shows the links

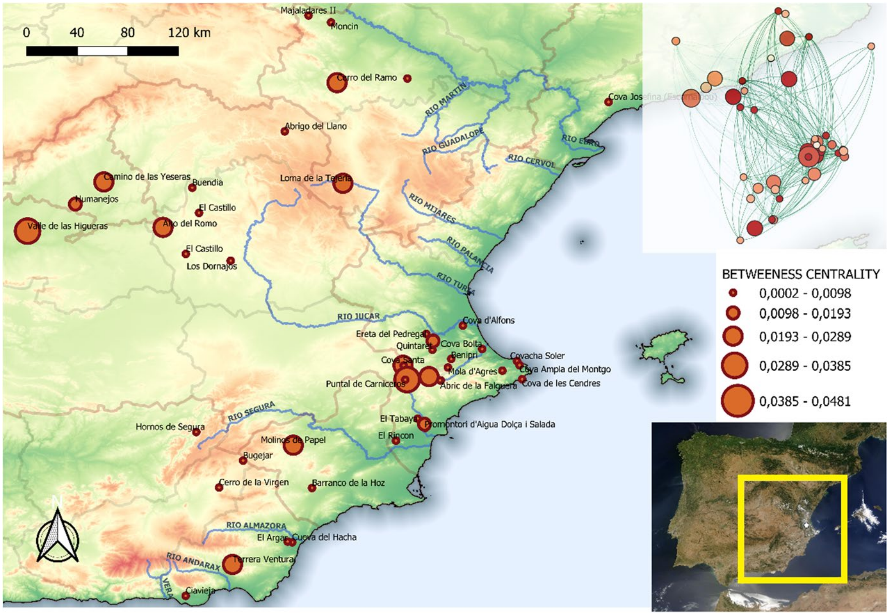


Fig. 8 Graph visualization of the networks corresponding to the nodes of the third period. The size indicates the betweenness centrality. The small window on the right shows the links

betweenness values are lower than in previous periods, something that reflects more distributed networks. This is a symptom of increased robustness and a certain degree of recovery. However, the average strength of the links is lower than in previous windows, which could be interpreted as a symptom of weakened information flows, enabling the appearance of local stylistic dissimilarities. The connections with the Ebro River appear to increase, but using the new route through the mountains of the Iberian System, marking the initial moment of the heterogeneous regional Bell Beaker styles, which tend to be associated with a more culturally fragmented world.

On one hand, the average betweenness presents a descending trajectory along the series. The average betweenness for the three periods is 0.038 for period 1, 0.043 for period 2, and 0.007 for period 3. The decreasing trend across the different windows can be related to many variables. For instance, the density increase (Table 4) might underlie the reduction of the betweenness detected. One interpretation that matches the archaeological record and the observations well points to an overall increase of links that could undermine the betweenness of specific bridging nodes in window 3, thus reducing the average betweenness. This could be considered an expression of the progressive small-world tendency that creates densely connected groups with weak ties to other communities, but this possibility will be further explored later.

Individual average betweenness seems to follow an exponential distribution in windows 1 and 2 and is unclear in 3 (Fig. 9). The maximum particular concentration can be found in window 2, together with the higher exponents, and occurs at the Los Millares and La Pedrera sites (which account for 50% of the total betweenness for that window). On the contrary, window 3 does not appear to follow an exponential

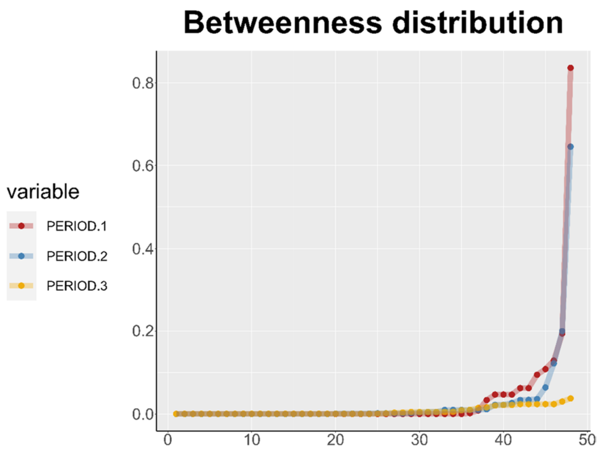


Fig. 9 Individual betweenness distribution, by periods

Table 4 Main structural metrics of the three networks

Cal BC	2550-2400	2400-2250	2250-2100
Nodes	43	29	47
Edges	245	185	722
Average degree with weight	6.739	5.069	9.083
Density	0.271	0.456	0.668
Average path length	1.992	1.601	1.332
Clustering	0.853	0.796	0.872
Average link weight	0.5913	0.4	0.27

distribution. That could be interpreted as the moment in which the tendency to develop scale-free networks is broken (Broido & Clauset, 2019), leading to a more distributed system, on the verge of the Bronze Age, but the reasons are still unclear.

Could this be caused by the concentration limit being exceeded? This limit of concentration could indicate an edge-of-change situation for the network. Is there any way of quantifying the limit for this concentration that could signal a turning point or a state shift? What are the reasons that drive these situations? All these questions must be addressed in upcoming research.

Further analysis will be conducted to get new perspectives and confirm the initial hypothesis: the existence of a highly connected and homogeneous world in the first period and a culturally fragmented one in the last. First, we have compared the network metrics of average path length and clustering to check the possibility of small-world situations (Watts & Strogatz, 1998). Figure 10 shows that the period with the greatest chance of a small-world structure is the third due to its high clustering and a lower average path length (Albert & Barabási, 2002).

In window 1, the clustering is high, but the average path length is high also, so we cannot speak of a small-world situation. Window 2 clustering reduction

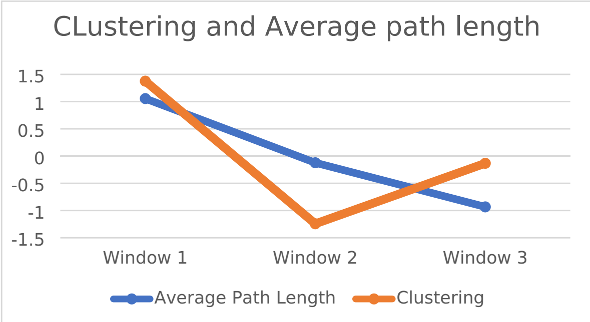


Fig. 10 Clustering and average path length (normalized) of the three periods

clearly shows this period's transitional role. The small-world status for window 3 means that very densely connected entities are related to other clusters through weak ties. The Fruchterman Reingold layout (Fruchterman & Reingold, 1991) illustrates this situation. In Fig. 11, the difference can be seen between periods 1 and 3 and the small-world effect for period 3. The color indicates the community, and the size shows the betweenness.

Clusters refer to highly connected entities that have a lesser between-group connection. This comparison shows that the information flow becomes far more evenly distributed and much less centralized over time. Periods 1 and 2 show far more scale-free networks than period 3 (Figs. 9 and 12). Clearly there is a breakdown of a hierarchical system visible in periods 1 and 2, leading to a more distributed small-world network in period 3. In addition, we have used different community detection analyses to contrast the results: Girvan-Newman (Despalatović *et al.*, 2014; Girvan

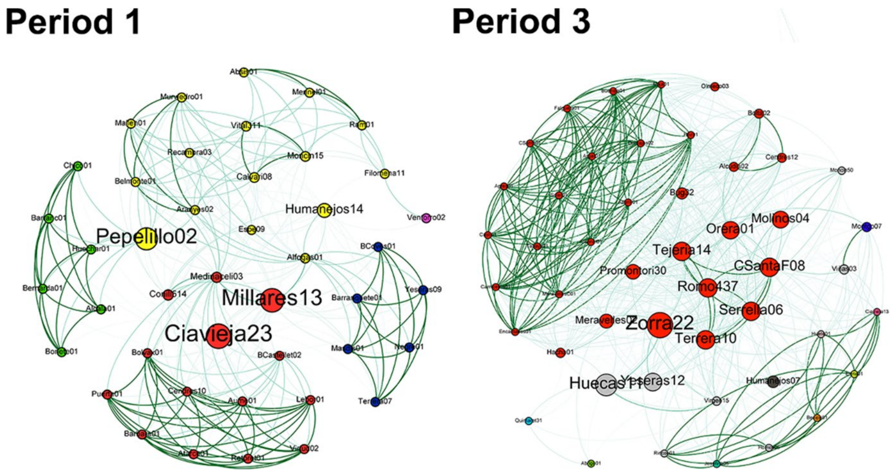


Fig. 11 Network corresponding to periods 1 and 3, with Fruchterman-Reingold layout. The color marks belonging to a community; the size marks the betweenness centrality

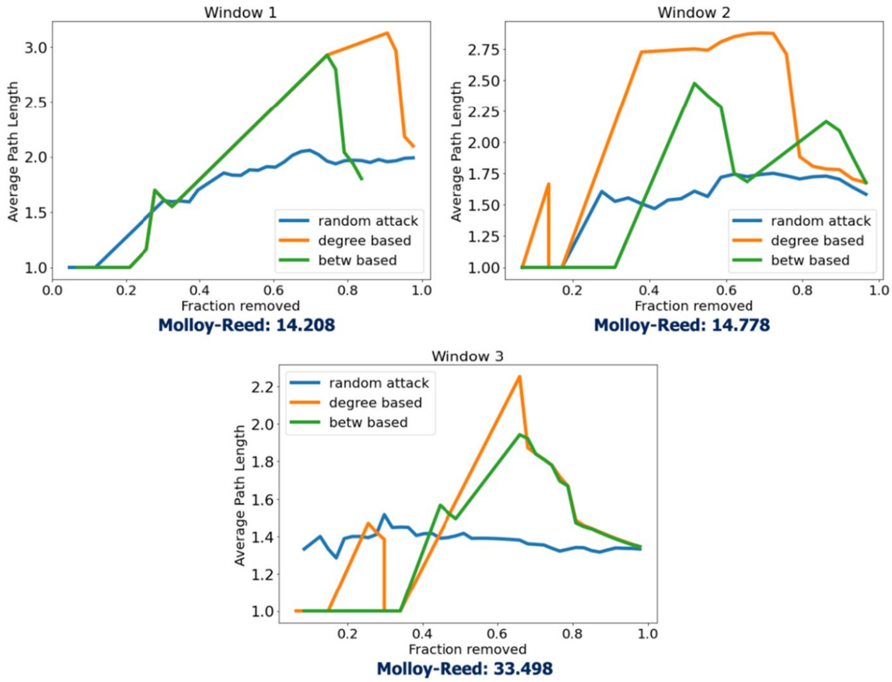


Fig. 12 Average path length evolution after removal of nodes from the giant component with three different attacks (random, degree, betweenness) for the three windows

& Newman, 2002) and statistical inference (Zhang & Peixoto, 2020). As can be seen in Table 5, the different algorithms find a similar number of communities across the three periods. We have employed these algorithms to quantify the communities present, not to detect geographical or cultural groups. According to the results, period one would be the most homogeneous due to the few communities found. The second period witnesses a noticeable increase in the clusters found; the third period clearly shows more significant fragmentation, illustrated by many clusters. It is necessary to point out that, as shown in Fig. 11, the network in window 3 is divided into two main groups connected by a third, playing a linking role. In period 1, the nodes connect the network with a higher betweenness centrality value. The connectivity in this period is dependent on these bottlenecks, which means that the network's topology could be linked to hierarchical topologies, as can also be seen in the metrics of Fig. 10.

Table 5 The number of communities detected by different algorithmic approaches

	Period 1	Period 2	Period 3
Size of the network (N)	43	29	48
Statistical inference	4	9	22
Girvan-Newman	5	9	17

To quantify this extent, we have carried out a twofold robustness test. On one hand, we have conducted a robustness analysis of the three networks, which involves attacking them by removing nodes. This procedure has been implemented with Python (Van Rossum & Drake, 2009) and the *networkX-robustness* package (Santanam, 2023). The attacks include random attacks and targeted attacks on nodes with the highest degree of centrality and betweenness centrality. Attack functions return the initial fraction of nodes in the giant component, the fraction of nodes in the giant component, and the average path length in the giant component after each node removal. By observing how the average path length changes as nodes are removed during an attack, we can gain insights into how resilient the network is to such attacks. If the average path length remains relatively stable even after significant node removal, it indicates that the network is more robust and able to maintain efficient communication pathways. A smaller average path length indicates that nodes in the network are more closely connected, allowing for efficient communication and information dissemination. On the other hand, a larger average path length suggests that the network becomes less efficient in transmitting information due to increased distances between nodes (Newman, 2012). We have also calculated the Molloy-Reed criterion (Cohen *et al.*, 2000), that helps determine the robustness of a network to complement the other metrics involved. It is based on the concept of degree distribution, which represents the frequency of nodes with different degrees. The Molloy-Reed criterion compares the actual degree distribution of a network to a random network with the same number of nodes and edges. If the network has a lower degree distribution than the random network, it suggests that the network is more vulnerable to attacks and failures. If the differences between the values of Molloy-Reed are large, it suggests that the networks or scenarios differ significantly in terms of robustness. The results can be followed in the new Fig. 12. The results corresponding to a random attack are clearly different for window 3, but those of the attack based on betweenness centrality are more similar in windows 2 and 3, which remain stable until 35% of the nodes are removed, than in window 1, which starts to collapse at the 20% mark. This clearly shows that window 1 is behaving as a scale-free network that is highly vulnerable to attacks on key nodes. On the contrary, windows 2 and 3 behave better when nodes with high betweenness are eliminated. This is confirmed by the Molloy-Reed criterion, which stays quite stable in windows 1 and 2, but increases dramatically in window 3, as can also be seen in Fig. 12.

In addition, we have performed a robustness test by applying successive edge weight filtering. The results show that the connectedness of the network corresponding to period 1 is more robust than the other two. We have manually removed 40% of the link weight for all periods using Gephi filtering tools. While 63.27% of the Period 1 network structure remains visible, only 21.08% of period 2 and 21.88% of period 3 do. It is a clear sign of the higher robustness of period 1 connections, which is also consistent with the homogeneity of the material record of the early Bell Beaker phase. These results are consistent with our initial premises and point to a crisis beginning in period 2 that lasts until period 3, despite the growth of the network. We have a first period with a more homogeneous culture and a third period characterized by a fragmented world with a small-world effect.

Discussion and Conclusions

All the evidence obtained from the analysis in this work points to the existence of two different periods in the Bell Beaker phase: the first period, in which the decorated vessels reached the Iberian Peninsula with remarkable homogeneity in all areas, and a late moment in which uniformity gave way to a culturally fragmented phase that ended with the Bronze Age. However, despite the climatic event known as the 4.2K (Bini *et al.*, 2019; Hinz *et al.*, 2019; Weinelt *et al.*, 2021) and the evidence of cultural regionalization in the Mediterranean area (Bernabeu & Martí, 1992; Bernabeu, 1984; Garrido-Pena, 1996; Juan-Cabanilles, 2005), it must be noted that recent studies have pointed to sustained demographic growth by the end of the Bell Beaker phase for the study area (Balsera, 2017; J. Bernabeu *et al.*, 2018; Blanco-González *et al.*, 2018). This situation is confirmed by our networks, whose size acts as a demographic proxy for the networks in SNA, noting a slight increase between the first and the third period, which is supposed to be a crisis moment. Looking at the networks in Fig. 12 and the distribution of betweenness in Fig. 9, it becomes clear that periods 1 and 2 have a scale-free distribution, which is especially vulnerable to the failure of crucial nodes that dominate the network structure.

In contrast, phase 3 is much less steeply distributed and can thus be equated far more with a small-world network, as the metrics showed. To summarize, for phase 1, we recognize a hierarchical network with predominant nodes; phase 2 still represents a hierarchical network, but one in which interconnectedness generally decreases significantly and represents an inflection point, and phase 3 forms a significantly less hierarchical network. According to the data considered, the crisis should thus be placed in phase 2, coinciding with the abovementioned 4.2K event, although it must be noted that the chronological resolution for this period is lower than for the other two. All these facts, together with the small-world situation detected in period 3, lead us to think about the last period and its culturally fragmented panorama in a different way. The period prior to the Bell Beaker phase was one of homogeneity in the area studied, as has been evidenced by previous SNA studies (Jiménez-Puerto, 2022a). Thus, period 1 represents a continuation of the dynamics from earlier moments. The resilience and metrics analyzed point to the consideration of period 1 (Fig. 13) as a moment of exploitation or growth (r-K) in which the emerging local elites embraced the Bell Beaker phenomenon as a way of justifying their rising position. In period 2, the information networks show a moment of crisis, clearly corresponding to a dissolution moment (Ω), whose causes are not clear but could be related to the climatic situation. On the other hand, period 3 represents a moment of continuation of the crisis, which seems to be unrelated to subsistence because the network clearly grows. Although the information does not flow as easily as in period 1, some signs of recovery can be seen in the metrics, and the small-world situation detected confirms this, so we consider this period to be a phase of reorganization (r). The causes of this regionalization seem to be the product of the internal dynamics of the system. The heterogeneity and abundance of decorated wares in this phase can be associated with

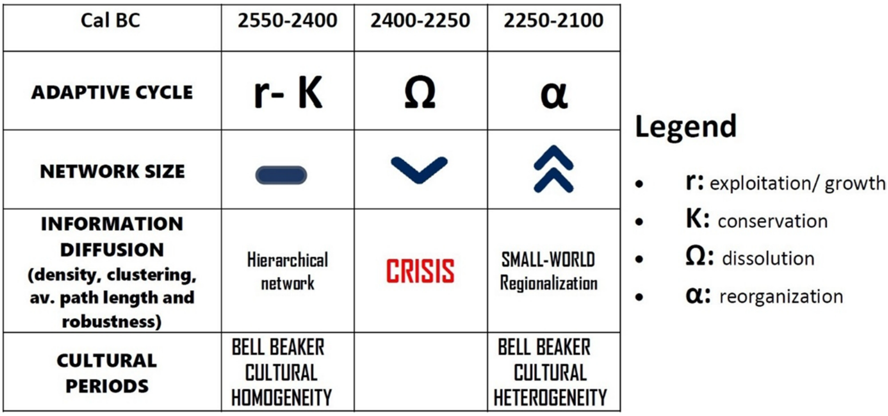


Fig. 13 Adaptive cycle proposal for the Bell Beaker phase in Eastern Iberia

a "democratization" of the Bell Beaker phenomenon, possibly associated with emulation. External causes cannot be ruled out either, however, due to the complexity of the situation for the Iberian Peninsula on the verge of the Bronze Age.

Recent studies on the development of exchange networks in the area during the transition to the Bronze Age have concluded that the flow of copper artifacts, far from declining, becomes more robust in the last period of the Bell Beaker phase (Jiménez-Puerto, 2022a). Recently, new genetic studies have added yet another dimension to this rather indistinct picture, proposing the appearance of new peoples coming from the Eurasian steppes (Olalde *et al*., 2019; Villalba-Mouco *et al*., 2021). All this research suggests that events taking place in the Bell Beaker phase and the transition to the Bronze Age were far more convoluted and complex than expected. Therefore, to properly assess the definition and impact of the Bell Beaker phenomenon, it would be necessary to increase the breadth of the chronological framework. That means including the periods just before and after its appearance and development in the analysis to get a more accurate background picture.

Finally, some habitation sites in which these decorated wares are absent share the same Bell Beaker chronology. This is especially true during the early phase, where the Bell Beaker phenomenon seems more related to the funerary world. Another approach should be tested to compensate for all these possible deviations, combining graves and habitats in the same model to enhance their fusion into new network nodes.

Our initial aim in this study was to propose an approach to ACM phase definition through SNA. Based on the metrics provided by SNA, we have proposed a phase definition explained in Fig. 12. Our proposal of using SNA in combination with Resilience Theory is still in its early stages, and future studies, which will attempt to refine this first approach, are still in progress. Consequently, some research lines are explored. One of the biggest challenges in archaeology is determining the relationships between artifacts. Social Network Analysis is a handy tool, with great potential, for dealing with relational information. In this study, we have proposed applying SNA to the problems associated with the Bell Beaker phase by analyzing the techniques of the decorated wares. The accuracy of the results has however been limited by some issues, derived mainly from the low resolution of the ^{14}C series (Crombé & Robinson, 2014; Peros *et al.*, 2010; Surovell *et al.*, 2009). We cannot forget the problems associated with the calibration curve in the period (Michczynski & Michczynska, 2006; Weninger *et al.*, 2015), which introduces a high uncertainty effect. Improving the absolute chronology associated with the Bell Beaker phenomenon should be a top priority for further development. Many more short-lived radiocarbon determinations coming from a closed context are needed to make it possible.

In addition to that, as many existing vessels emerge from altered contexts, another approach could be tested. For such wares, thermoluminescence analysis could be conducted. As it also requires the soils in which the pottery was found to be measured in order to calibrate and increase the accuracy, it should be performed at suitable sites (Arribas *et al.*, 1989; Liritzis *et al.*, 1994). The Cova de les Cendres (Teulada-Moraira, Alacant) provides a perfect context for conducting such an analysis.

Another challenge that must be addressed for SNA studies is related to the contemporaneity of the sites that share a chronological window. The resolution of the available radiocarbon series should be increased to create smaller chronological windows. The smaller size of the windows could improve the correct association of the synchronous sites present at a specific window, enhancing the results.

Although it is difficult, quantifying complexity could be another pathway to be explored in future works. It could help determine edge-of-chaos situations where the system works well and is resilient to disturbances (Carroll & Burton, 2000; Teuscher, 2022). There are some theoretical proposals to quantify complexity in networks, such as Von Neumann entropy (Petz, 2001). New studies suggest that the Kolmogorov complexity index might be a more consistent network method (Morzy *et al.*, 2017), which will be tested in future studies.

In addition, the study of the stylistic features of Bell Beaker decorations should be explored. We are currently working on defining formal styles found on vessels whose complete decoration can be traced. This approach could provide a more accurate idea of the relationships between the different communities since cultural transmission always take place in social contexts (Bentley & Shennan, 2003; White, 2013).

In this study, we have focused on ceramics through the study of decorative techniques, but further analysis of other proxies or artifacts should be conducted. A new SNA would be performed, but using multiplex networks. That would make it possible for multiple layers or networks (metallic, flint arrowheads, ideotechnic artifacts) to be integrated in a single analysis, confirming the results and creating a better picture for quantifying the complex processes of the Copper Age in the Iberian Peninsula.

All of these proposals are being considered in the ongoing Prometeo-Neonets project, in which the authors are involved, where studies are underway to extend the sample through the analysis of publications and materials in the eastern part of the Iberian Peninsula.

Acknowledgements We are very grateful to Aleksandr Diachenko, Jan-Erich Schlicht, and Miguel Sánchez for their editing and help. We also thank four anonymous reviewers for their comments and suggestions. Any errors or omissions are our own.

Code Availability All relevant codes are provided in the Supplementary Materials.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. This study has been funded under the research project Prometeo 2021/007: Neonets. A social network approach to understanding evolutive dynamics of neolithic societies (c. 5600-2000 cal BC), financed by the Valencian Ministry of Innovation, Universities, Science and Societies.

Data Availability The datasets generated by the research during the current study are available to the public under a Creative Commons license at the ZENODO repository, https://zenodo.org/record/8116301.

Declarations

Conflict of Interest The authors declare no competing interests.

References

Albert, R., & Barabási, A. (2002). Statistical mechanics of complex networks. *Reviews of Modern Physics, 74*, 47–97. https://doi.org/10.1103/RevModPhys.74.47

Alvares, D., Armero, C., & Forte, A. (2018). What does objective mean in a Dirichlet-multinomial process? *International Statistical Review, 86*(1), 106–118. https://doi.org/10.1111/insr.12231

Arribas, J., Calderón, T., & Blasco, C. (1989). Datación absoluta por termoluminiscencia: un ejemplo de aplicación arqueológica. *Trabajos de prehistoria, 46*, 231–246. https://doi.org/10.3989/tp.1989.v46.i0.595

Aura-Tortosa, J. E., Fernández, J., & Fumanal, M. P. (1993). Medio físico y corredores naturales: notas sobre el poblamiento paleolítico del País Valenciano. *Recerques del Museu d'Alcoi, 2*, 89–107.

Bailly, M., & Salanova, L. (1999). Les dates radiocarbone du Campaniforme en Europe occidentale: analyse critique des principales séries de dates. *Mémoires de la Société préhistorique française, 26*, 219–224.

Balsera, V. (2017). *Demografía y poblamiento en la meseta sur entre el 5500 y el 1200 cal BC. Una perspectiva desde el radiocarbono*. http://hdl.handle.net/10486/680470

Barroso Bermejo, R., Bueno Ramírez, P., Vázquez Cuesta, A., Odriozola Lloret, C. P., Uribelarrea del Val, D., López Jiménez, O., et al. (2015). Campaniforme no funerario en la provincia de Toledo: el yacimiento de Las Vegas. De nuevo el Valle de Huecas. *Trabajos de Prehistoria, 72*(1), 145–157. https://doi.org/10.3989/tp.2015.12148

Barthelemy, M. (2004). Betweenness centrality in large complex networks. *The European Physical Journal B - Condensed Matter, 38*(2), 163–168. https://doi.org/10.1140/epjb/e2004-00111-4

Barton, C. M. (2014). Complexity, social complexity, and modeling. *Journal of Archaeological Method and Theory, 21*(2), 306–324. https://doi.org/10.1007/s10816-013-9187-2

Bastian, M., Heymann, S., & Jacomy, M. (2009). *Gephi: An open-source software for exploring and manipulating networks*. https://doi.org/10.1609/icwsm.v3i1.13937

Bentley, R. A., & Maschner, H. D. G. (Eds.). (2003). *Complex Systems and Archaeology*. Univ. of Utah Press.

Bentley, R. A., & Shennan, S. J. (2003). Cultural transmission and stochastic network growth. *American Antiquity*, 459–485. https://doi.org/10.2307/3557104

Bernabeu, J. (1993). El III milenio a. C. en el País Valenciano: los poblados de Jovades (Cocentaina, Alacant) y Arenal de la Costa (Ontinyent, Valencia). *SAGVNTVM. Papeles del Laboratorio de Arqueología de Valencia, 26*, 9–179. https://doi.org/10.7203/SAGVNTVM

Bernabeu, J., Lozano, S., & Pardo-Gordó, S. (2017a). Iberian Neolithic Networks: the rise and fall of the Cardial World. *Frontiers in Digital Humanities, 4*. https://doi.org/10.3389/fdigh.2017.00007

Bernabeu, J., & Martí, B. (1992). El País Valenciano de la aparición del Neolítico al horizonte campaniforme. In Utrilla, M. & Maluquer, J. (Eds.) *Aragón/Litoral mediterráneo. Intercambios culturales durante la Prehistoria* (pp. 213–234).

Bernabeu, J., Balaguer, M., & Ll., Diez Castillo, A., and Orozco Köhler, T. (2006). Inequalities and Power. Three Millennia of Prehistory in Mediterranean Spain (5600 – 2000 cal BC). In P. Diaz del Río & L. García (Eds.), *Social Inequality in Iberian Late Prehistory* (pp. 97–116). . http://hdl.handle.net/10261/9740) .

Bernabeu, J., Moreno, A., & Barton, C. M. (2012). Complex systems, social networks, and the evolution of social complexity in the East of Spain from the Neolithic to Pre-Roman Times. In *The Prehistory of Iberia: Debating Early Social Stratification and the State* (pp. 53–73). Routledge.

Bernabeu, J. (1984). El vaso campaniforme en el Pais Valenciano. *Serie Trabajos Varios del SIP, 80*, 1–140.

Bernabeu, J., Guerra, M. R., & Balaguer, L. M. (2011). *Las primeras producciones cerámicas: el VI milenio cal aC en la península Ibérica*. Universitat de València. Departament de Prehistòria i Arqueologia.

Bernabeu, J., Jiménez-Puerto, J., Escribá, P., & Pardo-Gordo, S. (2018). C14 y poblamiento en las comarcas centro-meridionales del País Valenciano (c. 7000-1500 cal BC). *Recerques del Museu d'Alcoi*, *27*, 35–48. http://hdl.handle.net/10550/68657

Bernabeu, J., Manen, C., & Pardo-Gordó, S. (2017b). Spatial and temporal diversity during the Neolithic Spread in the Western Mediterranean: The first pottery productions. In O. García-Puchol & D. C. Salazar-García (Eds.), *Times of Neolithic Transition along the Western Mediterranean* (pp. 373–397). Springer International Publishing. https://doi.org/10.1007/978-3-319-52939-4_14

Bernabeu, J., Orozco, T. (2014). Hacia las sociedades complejas (IV y III milenio cal. BC) en la Iberia mediterránea. In Almagro, M. (Ed.) *Protohistoria de la Península Ibérica: del Neolítico a la Romanización* (pp. 71–81). Fundación Atapuerca.

Bianconi, G. (2018). *Multilayer Networks* (Vol. 1). Oxford University Press. https://doi.org/10.1093/oso/9780198753919.001.0001

Bini, M., Zanchetta, G., Perşoiu, A., Cartier, R., Català, A., Cacho, I., et al. (2019). The 4.2 ky BP event in the Mediterranean region: An overview. *Climate of the Past, 15*(2), 555–577. https://doi.org/10.5194/cp-15-555-2019

Blanco-González, A., Lillios, K. T., López-Sáez, J. A., & Drake, B. L. (2018). Cultural, demographic and environmental dynamics of the Copper and Early Bronze Age in Iberia (3300–1500 BC): Towards an interregional multiproxy comparison at the time of the 4.2 ky BP event. *Journal of World Prehistory, 31*(1), 1–79. https://doi.org/10.1007/s10963-018-9113-3

Blasco, C., Delibes, G., Baena, J., Liesau, C., & Ríos, P. (2007). The Calcolithic site of Camino de las Yeseras (San Fernando de Henares, Madrid): an advantageous context to study bell beakers in the central Iberian Peninsula. *Trabajos de Prehistoria*, *64*(1). https://doi.org/10.3989/tp.2007.v64.i1.99

Blasco, C., Rios, P., & Liesau, C. (2011). *Yacimientos calcolíticos con campaniforme de la región de Madrid: nuevos estudios*. Universidad Autónoma de Madrid Madrid.

Bollig, M. (2016). Adaptive cycles in the savannah: Pastoral specialization and diversification in northern Kenya. *Journal of Eastern African Studies, 10*(1), 21–44.

Boyd, R., Richerson, P. J. (1988). *Culture and the evolutionary process* (p. 339.). University of Chicago Press

Broido, A. D., & Clauset, A. (2019). Scale-free networks are rare. *Nature Communications, 10*(1), 1017. https://doi.org/10.1038/s41467-019-08746-5

Brughmans, T., & Poblome, J. (2012). Pots in space: Understanding Roman pottery distribution from confronting exploratory and geographical network analyses. In *New Worlds out of Old Texts: Developing Techniques for the Spatial Analysis of Ancient Narratives*.

Brughmans, T. (2013). Thinking through networks: A review of formal network methods in archaeology. *Journal of Archaeological Method and Theory, 20*(4), 623–662. https://doi.org/10.1007/s10816-012-9133-8

Brughmans, T., Keay, S., & Earl, G. (2015). Understanding inter-settlement visibility in Iron Age and Roman Southern Spain with Exponential Random Graph Models for Visibility Networks. *Journal of Archaeological Method and Theory, 22*(1), 58–143. https://doi.org/10.1007/s10816-014-9231-x

Bueno Ramírez, P., Barroso Bermejo, R., & De Balbín Behrmann, R. (2005). Beaker ritual, collective ritual: the Necropolis of artificial caves of the Higueras Valley, Huecas, Toledo. *Trabajos de Prehistoria*, *62*(2). https://doi.org/10.3989/tp.2005.v62.i2.69

Caraglio, A. (2020). How to redraw Bell Beaker networks in Southwestern Europe? *Préhistoires Méditerranéennes*, (8).

Caraglio, A., Ríos, P., & Liesau, C. (2022). A bipartite network analysis of Bell Beaker Decoration Diversity in Camino De Las Yeseras (Madrid, Spain). In *The Bell Beaker Culture in All Its Forms: Proceedings of the 22nd Meeting of 'Archéologie et Gobelets' 2021 (Geneva, Switzerland)* (p. 97). Archaeopress Publishing Ltd.

Carroll, T., & Burton, R. M. (2000). Organizations and complexity: Searching for the edge of chaos. *Computational & Mathematical Organization Theory, 6*(4), 319–337.

Clarke, D. L. (1976). The Beaker network-social and economic models. In *Glockenbecher Symposion (Oberried, 1974). Fibula-Van Dishoeck, Bussum-Haarlem* (pp. 460–477).

Cohen, R., Erez, K., ben-Avraham, D., & Havlin, S. (2000). Resilience of the Internet to random breakdowns. *Physical Review Letters, 85*(21), 4626–4628. https://doi.org/10.1103/PhysRevLett.85.4626

Collar, A. (2007). Network theory and religious innovation. *Mediterranean Historical Review, 22*(1), 149–162. https://doi.org/10.1080/09518960701539372

Collar, A., Coward, F., Brughmans, T., & Mills, B. J. (2015). Networks in Archaeology: Phenomena, abstraction, representation. *Journal of Archaeological Method and Theory, 22*(1), 1–32. https://doi.org/10.1007/s10816-014-9235-6

Cook, K. S., & Whitmeyer, J. M. (1992). Two approaches to social structure: Exchange theory and network analysis. *Annual review of Sociology, 18*(1), 109–127. http://www.jstor.org/stable/2083448

Coward, F. (2010). Small Worlds, Material Culture and Ancient Near Eastern Social Networks. In R. Dunbar, C. Gamble, & J. Gowlett (Eds.), *Social Brain, Distributed Mind* (pp. 448–479). https://doi.org/10.5871/bacad/9780197264522.003.0021

Crombé, P., & Robinson, E. (2014). 14 C dates as demographic proxies in Neolithisation models of northwestern Europe: A critical assessment using Belgium and northeast France as a case-study. *Journal of Archaeological Science, 52*, 558–566. https://doi.org/10.1016/j.jas.2014.02.001

Cunningham, D. (1973). Evaluation of replicable forms of instruction. A classification of information needs in formative and summative evaluation. *AV Communication Review, 21*(3), 351–367.

Despalatović, L., Vojković, T., & Vukičević, D. (2014). Community structure in networks: Girvan-Newman algorithm improvement. In *2014 37th international convention on information and communication technology, electronics and microelectronics (MIPRO)* (pp. 997–1002). IEEE. https://doi.org/10.1109/MIPRO.2014.6859714

Feinman, G. M. (2011). Size, complexity, and organizational variation: A comparative approach. *Cross-Cultural Research, 45*(1), 37–58. https://doi.org/10.1177/1069397110383658

Fenyvesi, K., & Lähdesmäki, T. (2017). *Aesthetics of Interdisciplinarity: Art and Mathematics*. Springer International Publishing. https://doi.org/10.1007/978-3-319-57259-8

Flannery, K. V. (1986). *The physical environment of the Guilá Naquitz cave group* (pp. 43–61). *Archaic Foraging and Early Agriculture in Oaxaca, Mexico, Academic Press, Orlando, FL.*

Folke, C. (2006). Resilience: The emergence of a perspective for social–ecological systems analyses. *Global Environmental Change, 16*(3), 253–267. https://doi.org/10.1016/j.gloenvcha.2006.04.002

Fruchterman, T. M., & Reingold, E. M. (1991). Graph drawing by force-directed placement. *Software: Practice and Experience, 21*(11), 1129–1164.

Furholt, M. (2020). Social worlds and communities of practice: A polythetic culture model for 3rd millennium BC Europe in the light of current migration debates. *Préhistoires Méditerranéennes, 8*. https://doi.org/10.4000/pm.2383

García-Atienzar, G. (2016). El Peñón de la Zorra (Villena, Alicante) y la caracterización del Campaniforme (2400-2100 cal AC) en el Alto Vinalopó. In *Del Neolític a l'Edat de Bronze en el Meditarrani occidental: estudis en homenatge a Bernat Martí Oliver* (pp. 365–378). Museu de Prehistòria de València.

García-Puchol, O., Molina, L, Cotino, F., Pascual-Benito, J. L., Orozco-Köhler, T., Pardo-Gordó, S., Carrión-Marco, Y, Pérez-Jordá, G., Clausi, M & Gimeno, L. (2014). *Hábitat, marco radiométrico y producción artesanal durante el final del Neolítico y el Horizonte Campaniforme en el corredor de Montesa (Valencia). Los yacimientos de Quintaret y Corcot. Archivo de Prehistoria Levantina*, *30*, 159–211. http://hdl.handle.net/10550/47134

García-Puchol, O., Bernabeu Auban, J., Carrión Marco, Y., Molina Balaguer, L., Perez Jorda, G., & Gómez Puche, M. M. (2013). *A funerary perspective on the Bell Beaker period in the Western Mediterranean. Reading the social context of individual burials at La Vital*. Gandia. https://doi.org/10.3989/tp.2013.12112

Garmezy, N. (1985). Competence and adaptation in adult schizophrenic patients and children at risk. In *Research in the Schizophrenic Disorders* (pp. 69–112). Springer.

Garrido-Pena, R., & Rojo-Guerra, M. (2014). Bell Beaker of the Iberian Penisula in its european context. In Marq (Ed.) *Campaniforme. Intercambio en la Prehistoria. Intercambio entre museos. MARQ* (pp. 11–22)

Garrido-Pena, R. (1996). Redes de intercambio entre el Sureste y el País Valenciano durante el Calcolítico: reflexiones en torno a un patrón decorativo campaniforme. *Complutum, 7*, 63–72.

Garrido-Pena, R. (2000). *El Campaniforme en la Meseta Central de la península ibérica (c. 2500-2000 AC.)* (Vol. 892). British Archaeological Reports International Series 892. Archaeopress (2000). https://doi.org/10.30861/9781841711546

Garrido-Pena, R., Flores Fernandez, R., Herrero-Corral, A. M., and Cambra-Moo, O. (2019). *Las sepulturas campaniformes de humanejos ()*.

Garrido-Pena, R., & López-Astilleros, K. M. (2000). Visiones sagradas para los líderes. Cerámicas campaniformes con decoración simbólica en la Península Ibérica. *Complutum*, (11), 285–300.

Girvan, M., & Newman, M. E. (2002). Community structure in social and biological networks. *Proceedings of the National Academy of Sciences, 99*(12), 7821–7826. https://doi.org/10.1073/pnas.122653799

Gjesfjeld, E. (2015). Network analysis of archaeological data from Hunter-Gatherers: Methodological problems and potential solutions. *Journal of Archaeological Method and Theory, 22*(1), 182–205. https://doi.org/10.1007/s10816-014-9232-9

Gronenborn, D., Strien, H.-C., Dietrich, S., & Sirocko, F. (2014). 'Adaptive cycles' and climate fluctuations: A case study from Linear Pottery Culture in western Central Europe. *Journal of Archaeological Science, 51*, 73–83. https://doi.org/10.1016/j.jas.2013.03.015

Harrison, R. J. (1977). *The bell beaker cultures of Spain and Portugal*. In Bulletin (Issue 35, pp. xx, 257). Peabody Museum of Archaeology and Ethnology, Harvard University. https://ehrafarchaeology.yale.edu/document?id=e050-007

Hinz, M., Schirrmacher, J., Kneisel, J., Rinne, C., & Weinelt, M. (2019). The Chalcolithic–Bronze Age transition in southern Iberia under the influence of the 4.2 ky event? A correlation of climatological and demographic proxies. *Journal of Neolithic Archaeology, 21*, 1–26. https://doi.org/10.12766/jna.2019.1

Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics, 4*(1), 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245

Holling, C. S., & Gunderson, L. H. (2002). Resilience and adaptive cycles. In Hollig C.S & Gunderson (Eds.) *Panarchy: Understanding transformations in human and natural systems* (pp. 25–62). http://hdl.handle.net/10919/67621

Jaccard, P. (1912). The distribution of the flora in the Alpine Zone.1. *New Phytologist, 11*(2), 37–50. https://doi.org/10.1111/j.1469-8137.1912.tb05611.x

Jacomy, A. (2011). Geolayout plugin for Gephi. *Github/ jacomyal / GeoLayout*. https://github.com/jacomyal/GeoLayout

Jiménez-Puerto, J. (2022a). *Conectando con el pasado. Redes sociales en la Prehistoria reciente. (Proquest.)*. University of Valencia https://www.proquest.com/docview/2742640164

Jiménez-Puerto, J. (2022b). *Bell Beaker data base for the Iberian Peninsula Eastern Seaboard*. Zenodo. https://doi.org/10.5281/zenodo.7904732

Jiménez-Puerto, J., and Bernabeu Aubán, J. (2023). Linking up Bell Beakers in the Iberian Peninsula: Supplementary material. Zenodo. https://doi.org/10.5281/ZENODO.8116301

Jiménez-Puerto, J., Bernabeu Aubán, J., and Orozco Köhler, T. (2018). Habitat evolution in the Iberian Eastern Seaboard, from Neolithic to the Bronze Age.

Jiménez-Puerto, J. (2018). *Redes, complejidad y arqueología: otra forma de ver el pasado*.

Jover-Maestre, F. J. J. & García-Atienzar, G. (2014). Del VI al III milenio cal BC: la configuración de nuevos espacios sociales en el valle del Vinalopó. In Jover-Maestre, F. J. J., Torregrosa, P. & García-Atiénzar, G. (Eds.) *El Neolítico en el Bajo Vinalopó*. Archaeopress.

Juan-Cabanilles, J. J. (2005). Las manifestaciones del Campaniforme en el País Valenciano: una visión sintética. In *El campaniforme en la Península Ibérica y su contexto europeo. Bell Beakers in the Iberian Peninsula and their European context* (pp. 389–400). Secretariado de Publicaciones e Intercambio Editorial.

Kanders, K., Lorimer, T., & Stoop, R. (2017). Avalanche and edge-of-chaos criticality do not necessarily co-occur in neural networks. *Chaos: An Interdisciplinary Journal of Nonlinear Science, 27*(4), 047408. https://doi.org/10.1063/1.4978998

Kleijne, J. P. (2019). *Embracing Bell Beaker. Adopting New Ideas and Objects Across Europe During the Later 3rd Millennium BC (c. 2600-2000 BC)*. Sidestone Press.

Knappett, C. (2011). *An archaeology of interaction: network perspectives on material culture and society*. In *Oxford*. Oxford University Press.

Knappett, C., Evans, T., & Rivers, R. (2008). Modelling maritime interaction in the Aegean Bronze Age. *Antiquity, 82*(318), 1009–1024. https://doi.org/10.1017/S0003598X0009774X

Langton, C. G. (1990). Computation at the edge of chaos: Phase transitions and emergent computation. *Physica D: Nonlinear Phenomena, 42*(1–3), 12–37. https://doi.org/10.1016/0167-2789(90)90064-V

Lanos, P., & Philippe, A. (2018). Event date model: a robust Bayesian tool for chronology building. *Communications for Statistical Applications and Methods, 25*(2), 131–157. https://doi.org/10.29220/CSAM.2018.25.2.131

Vibet, M. A., Philippe, A., Lanos, P., & Dufresne, P. (2016). *Chronomodel: Chronological modelling of archaeological data using Bayesian statistics.(version 1.5).* http://www.chronomodel.fr

Lemercier, O. (2011). Le guerrier dans l'Europe du 3er millénaire avant notre ère. L'arc et le poignard dans les sépultures individuelles campaniformes, In Baray, L., Hohegger, M., Dias-Merinho, M. & Guilaine, J. (Eds.), *L'armement et l'image du guerrier dans les sociétés anciennes. De l'objet à la tombe* (pp. 121–166).

Lemercier, O. (2002). Le Campaniforme dans le sud-est de la France. De l'Archéologie à l'Histoire du troisième millénaire avant notre ère. *Bulletin de la Société préhistorique française, 99*(3), 635–639. https://doi.org/10.4000/pm.279

Lemercier, O. (2018). Think and act. Local data and global perspectives in Bell Beaker archaeology. *Journal of Neolithic Archaeology, 20*, 77–96. https://doi.org/10.12766/jna.2018S.5

Liesau, C., and Blasco, C. (2011). Materias primas y objetos de prestigio en ajuares funerarios como testimonios de redes de intercambio en el Horizonte campaniforme.

Lillios, K. T., Blanco-González, A., Drake, B. L., & López-Sáez, J. A. (2016). Mid-late Holocene climate, demography, and cultural dynamics in Iberia: A multi-proxy approach. *Quaternary Science Reviews, 135*, 138–153. https://doi.org/10.1016/j.quascirev.2016.01.011

Liritzis, I., Galloway, R., & Theocaris, P. (1994). Thermoluminescence dating of ceramics revisited: optical stimulated luminescence of quartz single aliquot with green light-emitting diodes. *Journal of Radioanalytical and Nuclear Chemistry, 188*(3), 189–198. https://doi.org/10.1007/bf02164592

Liu, J.-G., Hou, L., Pan, X., Guo, Q., & Zhou, T. (2016). Stability of similarity measurements for bipartite networks. *Scientific Reports, 6*(1). https://doi.org/10.1038/srep18653

López-Padilla, J. A. (2006). Consideraciones en torno al "Horizonte Campaniforme de Transición." *Archivo de prehistoria levantina*, (XXVI*)*. 193–243

Lull, V., Micó, R., Rihuete, C., and Risch, R. (2010). Límites históricos y limitaciones del conocimiento arqueológico: la transición entre los grupos arqueológicos de Los Millares y El Argar. In Sánchez, F. J., Bueno, P., Gilman, A. and Martín, C. (Eds.) *Arqueología, Sociedad, Territorio y Paisaje. Estudios sobre Prehistoria Reciente, Protohistoria y transición al mundo romano en homenaje a Mª Dolores Fernández Posse* (pp. 75–94).

Lull, V., Micó, R., Rihuete, C., Risch, R., Meller, H., Bertemes, F., & Bork, H. (2013). In H. Meller, F. Bertemes, H. R. Bork, & R. Risch (Eds.), *Political collapse and social change at the end of El Argar* (pp. 283–302).

Michczynski, A., & Michczynska, D. J. (2006). The effect of PDF peaks height increase during calibration of radiocarbon date sets. *Geochronometria, 25*, 1–4.

Miller, J. H., Page, S. E. (2007). *Complex adaptive systems: An introduction to computational models of social life* (p. 284). Princeton University Press.

Mitchell, M. (2009). *Complexity: a Guided Tour*. In *Oxford [England]*. Oxford University Press.
Molina, F., Cámara, J. A., Capel, J., Nájera, T., & Sáez, L. (2004). Los Millares y la periodización de la Prehistoria Reciente del Sureste. *Simposios de Prehistoria Cueva de Nerja, 2*, 142–158.
Molina, F., Mederos, A., Delgado-Huertas, A., Cámara, J. A., Peña, V., Martínez, R. M., et al. (2020). La necrópolis calcolítica de Los Millares: dataciones radiocarbónicas y valoración de la dieta y del medio ambiente a partir del análisis de isótopos estables. *Trabajos de Prehistoria, 77*(1), 67. https://doi.org/10.3989/tp.2020.12247
Moran, E. F. (1990). *The ecosystem approach in anthropology: From concept to practice*. University of Michigan Press.
Morzy, M., Kajdanowicz, T., & Kazienko, P. (2017). On measuring the complexity of networks: Kolmogorov complexity versus entropy. *Complexity, 2017*, 1–12. https://doi.org/10.1155/2017/3250301
Newman, M. (2012). *Networks: An introduction*. Oxford university press.
O'Brien, M. J., & Lyman, R. L. (2000). *Applying evolutionary archaeology: A systematic approach*. Springer Science and Business Media.
O'Brien, M. J., & Shennan, S. (2010). *Innovation in cultural systems: Contributions from evolutionary anthropology*. MIT Press.
Olalde, I., Mallick, S., Patterson, N., Rohland, N., Villalba-Mouco, V., Silva, M., et al. (2019). The genomic history of the Iberian Peninsula over the past 8000 years. *Science, 363*(6432), 1230–1234. https://doi.org/10.1126/science.aav4040
Pardo-Gordó, S., Bernabeu Aubán, J., Jiménez-Puerto, J., Armero, C., & García-Donato, G. (2022). The chronology of archaeological assemblages based on an automatic Bayesian procedure: Eastern Iberia as a study case. *Journal of Archaeological Science, 139*, 105555. https://doi.org/10.1016/j.jas.2022.105555
Pascual Beneyto, J., Barberà, M., & Ribera, A. (2005). Camí de Missena (La Pobla del Duc): un interesante yacimiento del III milenio en el País Valenciano. In Ontañón, R., García-Moncó, C. & Arias, P. (Eds.) *Actas del III Congreso del Neolítico en la Península Ibérica* (pp. 803–814).
Pascual-Benito, J. L. (1998). *Utillaje óseo, adornos e ídolos neolíticos valencianos*. Diputación Provincial de Valencia, Servicio de Investigación Prehistórica.
Pérez Ripoll, M. (1999). La explotación ganadera durante el III milenio a. C. en la Península Ibérica. *Sagvntvm Extra, 2*, 95–103.
Pérez-Jordá, G., Bernabeu, J., García-Carrión, Y., García-Puchol, O., Molina Ll., Gómez, M. (2011) (Eds.) *La Vital (Gandía, Valencia). Vida y muerte en la desembocadura del Serpis durante el III y el I milenio AC*. Serie de Trabajos Varios (Vol. 113, p. 280).
Pérez-Jordà, G., Peña-Chocarro, L., & Pardo-Gordó, S. (2021). Fruits arriving to the west. Introduction of cultivated fruits in the Iberian Peninsula. *Journal of Archaeological Science: Reports, 35*, 102683. https://doi.org/10.1016/j.jasrep.2020.102683
Peros, M. C., Munoz, S. E., Gajewski, K., & Viau, A. E. (2010). Prehistoric demography of North America inferred from radiocarbon data. *Journal of Archaeological Science, 37*(3), 656–664. https://doi.org/10.1016/j.jas.2009.10.029
Petz, D. (2001). Entropy, Von Neumann and Von Neumann Entropy. In M. Rédei & M. Stöltzner (Eds.), *John von Neumann and the Foundations of Quantum Physics* (pp. 83–96). Springer Netherlands. https://doi.org/10.1007/978-94-017-2012-0_7
Qin, J., Wu, H., Tong, X., & Zheng, B. (2013). A quantitative method for determining the robustness of complex networks. *Physica D: Nonlinear Phenomena, 253*, 85–90. https://doi.org/10.1016/j.physd.2013.03.002
Rappaport, R. A. (1971). *Pigs for the ancestors: Ritual in the ecology of a New Guinea People*. Waveland Press.
Ríos, P., Blasco, C., Aliaga, R. (2011). Entre el Calcolítico y la Edad de Bronce. Algunas consideraciones sobre la cronología campaniforme. *Cuadernos de Prehistoria y Arqueología de la Universidad Autónoma de Madrid, 38*, 195–208.
Rojo-Guerra, M. A., Garrido-Pena, R., & de Lagrán, Í. G.-M. (2008). No sólo cerveza. Nuevos tipos de bebidas alcohólicas identificados en análisis de contenidos de cerámicas campaniformes del Valle de Ambrona (Soria). *Cuadernos de Prehistoria y Arqueología de la Universidad de Granada, 18*, 91–105. https://doi.org/10.30827/cpag.v18i0.741
Rojo-Guerra, M., Garrido-Pena, R., de Lagrán, G.-M., & Í. (Eds.). (2005). *El Campaniforme en la Península Ibérica y su contexto europeo =: Bell beakers in the Iberian Peninsula and their European context*. Universidad de Valladolid, Secretariado de Publicaciones e Intercambio Editorial.
Rovira, S., and Montero, I. (1994). Metalurgia campaniforme y de la Edad del Bronce en la Comunidad de Madrid.

Salanova, L. (2005). The origins of the Bell Beaker phenomenon: Breakdown, analysis, mapping. *El campaniforme en la Península Ibérica y su contexto europeo/Bell Beakers in the Iberian Peninsula and their European context. Serie Arte y Arqueología, 21*, 29–60.
Santanam, T. (2023). tsantanam/networkx-robustness: v0.0.7. Zenodo. https://doi.org/10.5281/ZENODO.7855211
Sherrat, A. (1987). Cups that cheered. Bell Beakers of the Western Mediterranean. *Bar International Series, 331*, 81–103.
Sindbæk, S. (2007). The small world of the vikings: Networks in early Medieval communication and exchange. *Norwegian Archaeological Review, 40*(1), 59–74. https://doi.org/10.1080/00293650701327619
Suarez-Otero, J. (1996). Cerámica campaniforme con decoración cordada en la Península Ibérica: acotaciones en torno a una problemática. *Boletín auriense, 26*, 27–46.
Surovell, T. A., Finley, J. B., Smith, G. M., Brantingham, P. J., & Kelly, R. (2009). Correcting temporal frequency distributions for taphonomic bias. *Journal of Archaeological Science, 36*(8), 1715–1724. https://doi.org/10.1016/j.jas.2009.03.029
Teuscher, C. (2022). Revisiting the edge of chaos: Again? *Biosystems, 218*, 104693. https://doi.org/10.1016/j.biosystems.2022.104693
Van den Berg, K. A. M. (2014). Network analysis in archaeology: New approaches to regional interaction. *Norwegian Archaeological Review, 47*(2), 220–223. https://doi.org/10.1080/00293652.2014.960446
Van Rossum, G., & Drake, F. L. (2009). *Python 3 Reference Manual*. CreateSpace.
Villalba-Mouco, V., Oliart, C., Rihuete-Herrada, C., Childebayeva, A., Rohrlach, A. B., Fregeiro, M. I., et al. (2021). Genomic transformation and social organization during the Copper Age–Bronze Age transition in southern Iberia. *Science Advances, 7*(47), eabi7038. https://doi.org/10.1126/sciadv.abi7038
Walker, B., Carpenter, S., Anderies, J., Abel, N., Cumming, G., Janssen, M., et al. (2002). Resilience management in social-ecological systems: A working hypothesis for a participatory approach. *Conservation Ecology, 6*(1).
Washburn, D. K., Crowe, D. W., & Ahlstrom, R. V. (2010). A symmetry analysis of design structure: 1,000 years of continuity and change in Puebloan ceramic design. *American Antiquity*, 743–772. https://doi.org/10.7183/0002-7316.75.4.743
Wasserman, S., & Faust, K. (1994). *Social network analysis: Methods and applications*. Cambridge University Press.
Watts, D. J., & Strogatz, S. H. (1998). Collective dynamics of "small-world" networks. *Nature, 393*, 440–442.
Weinelt, M., Kneisel, J., Schirrmacher, J., Hinz, M., & Ribeiro, A. (2021). Potential responses and resilience of Late Chalcolithic and Early Bronze Age societies to mid-to-late Holocene climate change in the southern Iberian Peninsula. *Environmental Research Letters, 16*(5), 055007.
Welsch, R., & Terrell, J. (1998). Material culture, social fields, and social boundaries on the Sepik Coast of New Guinea. In Stark, M. (Ed.) *The Archaeology of Social Boundaries*, Smithsonian series in Archaeological Inquiry (pp. 50–77).
Weninger, B., Clare, L., Jöris, O., Jung, R., & Edinborough, K. (2015). Quantum theory of radiocarbon calibration. *World Archaeology, 47*(4), 543–566. https://doi.org/10.1080/00438243.2015.1064022
White, A. (2013). An abstract model showing that the spatial structure of social networks affects the outcomes of cultural transmission processes. *Journal of Artificial Societies and Social Simulation, 16*(3). https://doi.org/10.18564/jasss.2219
Wilbert, J. (1993). Mystic endowment: Religious ethnography of the Warao Indians.
Wobst, H. M. (1976). Locational relationships in Paleolithic society. *Journal of Human Evolution, 5*(1), 49–58.
Zhang, L., & Peixoto, T. P. (2020). Statistical inference of assortative community structures. *Physical Review Research, 2*(4), 043271. https://doi.org/10.1103/PhysRevResearch.2.043271

The online version contains supplementary material available at https://zenodo.org/record/8116301.