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The chronology of archaeological assemblages based on an automatic Bayesian procedure: Eastern Iberia as study case

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A B S T R A C T

The purpose of this work is to show an automatic Bayesian procedure to obtain accurate chronological information of archaeological assemblages characterized by palimpsest or without radiocarbon dates and whose temporal information comes only from bifacial flint arrowheads.

In this paper, a classification method based on the Dirichlet-multinomial inferential process and its posterior predictive probability distribution is discussed. Its purpose is to predict the chronological period of undated archaeological assemblages (levels or sites) by means of a Bayesian predictive process based on the posterior distribution of each bifacial flint arrowhead types in the Eastern Iberia during the 4th and 3rd millennium cal. BC. The results obtained suggest that this approach is very useful to achieve an accurate chronology when other archaeological information is not available, or it is not conclusive.

1. Introduction

Bayesian statistical methodology is widely used by archaeologists to analyze and interpret radiocarbon dates (Bronk Ramsey, 2009), although it has also been developed for other absolute dating methods such as electron spin resonance (Millard, 2006), dendrochronology (Litton and Zainodin, 1991; Millard, 2002) or, more recently, luminescence (Zink, 2015). The rise of Bayesian methods is mainly due to two factors. On one hand, it allows combining absolute chronology such as ^{14}C dates and relative chronology like stratigraphic context (Buck et al., 1991). On the other hand, some calibration software has Bayesian options that allow users (archaeologists) to standardize the intrinsic statistical concepts and the computational techniques used to implement them (Buck and Juarez, 2017, 2020).

The application of Bayesian methods in the archaeological field has increased notably in recent decades because many archaeologists go beyond the simple 'eye-balling' of a set of calibrated dates (Bayliss, 2015; Hamilton and Krus, 2018). In this sense, Bayesian methods have a wide range of applications such as the modelling of archaeological chronologies and cultural transition phenomena from radiocarbon information (Aranda Jiménez et al., 2018; Binder et al., 2017; Conneller et al., 2016; García Puchol et al., 2018; Pérez Jordà et al., 2021; Pettitt and Zilhão, 2015; Riede and Edinborough, 2012; Whittle et al., 2011 among others), spatial analysis (Robertson, 1999), geophysical survey (Buck et al., 1996), site locations/evaluation based on Bayesian Information Criterion (Finke et al., 2008; Visentin and Carrer, 2017) and recently to explore trends in paleodemography (Crema and Shoda, 2021). However, Bayesian methods have limited scope for seriation-like age estimates from archaeological materials. On one hand there are model-based Bayesian procedures (see Dearden et al., 2013 for method details) which uses stochastic tools such as Monte Carlo Markov Chain methods to approximate non-analytical posterior distributions (see Buck and Sahu, 2000; Halekoh and Vach, 1999 for archaeological approaches). On the other hand, empirical-based Bayesian approaches (Carlin and Louis, 1997) compute a prior probability from the density of dated assemblages and then uses it to estimate the posterior probability of an undated sample (see Fernández-López de Pablo and Barton, 2015; Gironès Rofes et al., 2020; Ortman et al., 2007; Snitker et al., 2018 for

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some applications).

The objective of this paper is to present and apply an automatic Bayesian procedure based on posterior predictive distributions to provide an accurate chronology to sites that have neither absolute chronology nor clear stratigraphy. This approach is applied to archaeological sites located in the East of the Iberian Peninsula during the 4th and 3rd millennium cal. BC using the bifacial flint arrowhead as archaeological proxy because its shape has temporal implications (Juan Cabanilles, 2008).

2. Geographical and archaeological scope

The archaeological information used here (Fig. 1) comes from Eastern Spain. This region is one of the best-known in the Iberia Peninsula for the study of the Late Prehistory (Bernabeu, 1993; Bernabeu et al., 2017a). The study area is defined by the Ebro River in the North and the Segura River in the South. This territory offers very varied landscapes that encompass the mountainous interior, due to the Iberian and Prebetica mountain ranges, and the coastal platform between Ebro and Segura rivers. Thus, the Eastern Spain is characterized by the geographical contrast between abrupt mountainous areas and a variable littoral extension, in which natural corridors, such as rivers and coastal plains, constitute the routes that connect the different territories (Aura Tortosa et al., 1993).

The chronological sequence of the Late Prehistory of Eastern Iberia falls within the 6th to 2nd millennia cal. BC. This sequence includes several cultural horizons based on comparative stratigraphy, radiocarbon dates, and changes in pottery decoration provided by the Cova de l'Or and the Cova de les Cendres (Bernabeu, 1989; Martí et al., 1980). In this work we will focus on the Late Neolithic and Chalcolithic (4th-3rd millennium cal. BC). This is a period characterized by the presence of settlements located in endorheic zones with the presence of ditches and structures excavated in the ground (silos and pits) for different uses, including the storage of agricultural resources (Bernabeu Aubán and Orozco Kohler, 2014). During this period, changes were documented on an economic and social scale. On one hand, the available archaeobotanical record suggests a change in the agricultural model characterized by extensive agriculture (Pérez Jordá and Peña Chocarro, 2013), whilst archaeozoological remains show an increase in cattle, which were used not only to obtain secondary products such as milk, but also as a work force according to the pattern of sacrifice and the presence of bone pathologies (Pérez Ripoll, 1999). On the other hand, a change began in the funerary pattern characterized by multiple burials in caves (Soler Díaz, 2002), although in some settlements individual burials in pits have been also documented (Pascual Beneyto, 2010). Likewise, the social inequality observed both in the evidence of appropriation of agricultural

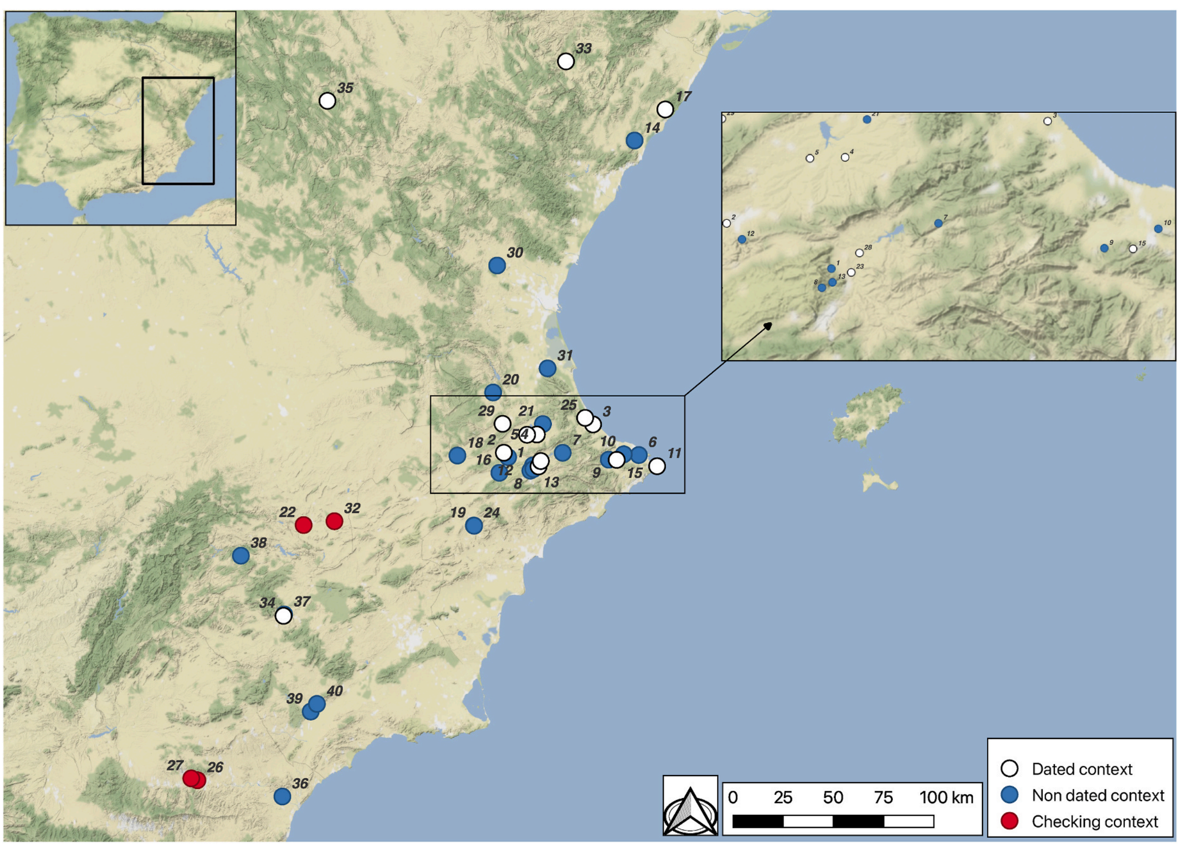

Fig. 1. Map of the region with archaeological sites. (1) Escurrupènia, (2) Arenal de la Costa, (3) B. Beniteixir, (4) Camí de Missena, (5) Colata, (6) Ampla del Montgó, (7) En Pardo, (8) Aranyes, (9) Barranc de la Parra, (10) Barranc de Càfer, (11) Barranc del Migdia, (12) Garrofer, (13) Negre, (14) Petrolí, (15) Randero, (16) Anells, (17) Diablets, (18) Cova Santa, (19) Casa Colorá, (20) Ereta Pedregal, (21) Font de Mahiques, (22) Fuente Isso, (23) Jovades, (24) Torreta-Monestil, (25) Vital, (26) Llanos del Jautón, (27) Los Chruletes, (28) Niuet, (29) Quintaret, (30) Rambla Catellarda, (31) Sima de la Pedrera, (32) Vilches IV (33) Mas Cremat, (34) Molinos de Papel, (35) El Castillo, (36) Campos, (37) Camino del Molino, (38), A. Tóbar, (39) Murviedro 1, (40) Cueva Sagrada. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

surpluses (Pérez Jordà et al., 2011) and in the restricted circulation of different raw materials and prestige objects (Orozco Köhler 2000; Rovira Llorens and Montero Ruiz, 2011). In short, during the 4th millennium a process of social complexification began that reached its climax at the end of the 3rd millennium (Bernabeu et al., 2006, 2013).

3. Material and Methods

As indicated in the Introduction, we present a statistical Bayesian procedure which focuses on flint lithic bifacial arrowheads. They constitute a chronological marker during the Late Neolithic/Chalcolithic and are widely represented both in habitat context (Bernabeu, 1993; Bernabeu et al., 1994), including the whole operative chain of their elaboration at the site of Ereta del Pedregal (Juan Cabanilles, 1994), and in funerary contexts (García Puchol and McClure, 2010; McClure et al., 2010; Soler Díaz, 1999).

The classification of the arrowheads is based on seven types (Fig. 2) following the morphological criteria defined by Juan-Cabanilles (2008) and which we briefly describe below:

Type 1 (*rhomboid/rhombus-eye shape*). This class corresponds to rhomboid-shaped arrowheads. They are the most basic types of assemblage present in the European context and are individualized by the shape of the base and the shape of the point.

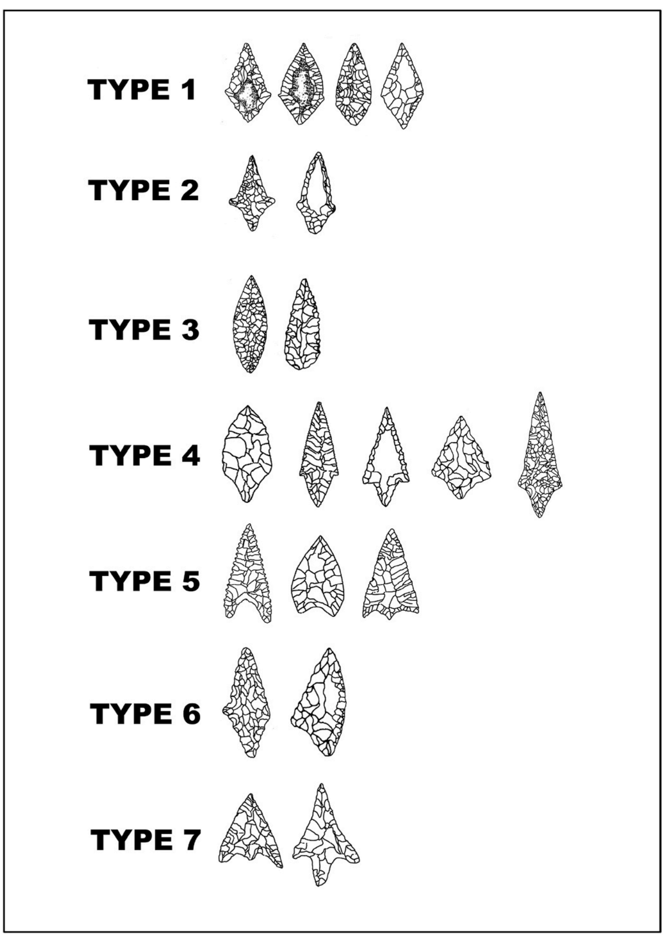

Fig. 2. Flint arrowhead types. Compilation based on Juan Cabanilles (2008) and Borrego et al. (1992).

Type 2 (cruciform or with side appendages). Arrowheads with lateral appendages and more stylized cruciform arrowheads belong to this type.

Type 3 (leaf-like). All those in this group are characterized by their leaf-like shape. The base may be round or pointed.

Type 4 (peduncle without barbs). This class includes all arrowheads with a thinned base or a peduncle. The point may be triangular or lancet-shaped. Those with a thinned base have a variable 'shoulder' which can be classified in those with a flat shoulder or those with an acute angle.

Type 5 (concave base). Arrowheads of this class vary in shape from triangular to more curved, but all of them have in common a concave base. In addition, there may sometimes be an emerging peduncle.

Type 6 (asymmetric). This class is the most unusual class and consists of asymmetrically shaped arrowheads, with or without lateral appendages.[1]

Type 7 (barbed and tanged). This type consists of all those arrowheads which have a peduncle with barbs. We have considered as barb all those that go beyond the base of the triangle. Depending on the peduncle there are two kinds: those with a peduncle larger than the barb or those with a peduncle smaller than the barb.

3.1. Archaeological sites for the inferential process

The archaeological sample used to carry out the inferential process, i.e., the Bayesian learning process, was selected following this procedure: firstly, archaeological sites/levels with a clear association between stratigraphy and arrowheads were considered. Once identified, those with ^{14}C dates made on short-life samples were selected. Finally, new radiocarbon dates were carried out to provide a large archaeological sample with an accurate chronology. To sum up, we have chosen 29 levels with 36 ^{14}C dates related to 14 archaeological sites that are available in Table 1.

According to the chronostratigraphic information and the evolution of the arrowheads, we have organized our archaeological sample in five time periods with an estimated duration computed from Bayesian radiocarbon modelling (for details of the chronological Bayesian model see the Supplementary Material):

Period I contains the oldest level of the ditch A at Niuet (Bernabeu et al., 1994) and the oldest layer of silos 129 (layer 3) and 156 at Jovades (Bernabeu, 1993).

Period II is defined by information from silo Q228 at Quintaret (García Puchol et al., 2014), layer 18 of ditch A at Niuet, silo 129 (layer 2) and silo 163 at Jovades, and the pits E1 and E72 at Colata (Gómez Puche et al., 2004).

Period III combines information from the upper layers of the Niuet ditch and from different funerary contexts such as Barranc del Migdia II (Soler Díaz et al., 2016), Barranc de Beniteixir pit E21 (Pascual Beneyto, 2010), La Vital (group 2) (Pérez Jordà et al., 2011), Cova de Randero (Soler Díaz et al., 2016), Cova dels Diablets (Aguilella Arzo et al., 1999, 2014) and some information from group 11/23/52/53 from Camí de Missena (Bernabeu et al., 2017b; Pascual Beneyto, 2005) and Cingle del Mas Cremat, Level II (Vizcaino León, 2010).

Period IV is defined by information from group 51/62 from Camí de Missena (Bernabeu et al., 2017b; Pascual Beneyto, 2005), group 5 from La Vital (Pérez Jordà et al., 2011) and Barranc del Migdia III/IV (Soler Díaz et al., 2016).

Period V contains the upper level from Arenal de la Costa (Bernabeu, 1993; Diez Castillo, 2011), group 8 from La Vital (Pérez Jordà et al.,

[1] It is important to notice that many broken arrowheads can look like *asymmetrical* assemblages. Caution is needed when including an arrowhead in this group.

Table 1
Archaeological levels and radiocarbon dates used to apply the Bayesian learning process.

Site	Level	Id^{14}C	BP	±	Sample	Arrows	Reference
Arenal de la Costa	BXV/A2	Beta-228894	3700	40	S	4	Diez Castillo (2011)
Barranc de Beniteixir	Pit 21	Beta-244534	4100	40	HB	1	Pascual Beneyto (2010)
Colata	Pit 1 (SU 3001)	AA-59520	4335	36	S	1	Gómez Puche et al. (2004)
	Pit 72 (SU 3057)	AA-59521	4463	36	S		
Cova dels Diablets	II (Q1)	MAMS-18650	4197	21	HB	5	Aguilella Arzo et al. (2014)
	I (Q1)	MAMS-18651	4141	21	HB		
	I	MAMS-18652	4143	21	HB		
Jovades	Pit 156 (lyr. 1)	CNA-48371.1	4464	39	S	2	This work
	Pit 129 (lyr. 3)	CNA-48361.1	4591	39	S	2	
	Pit 129 (lyr. 2)	CNA-48351.1	4387	39	S	2	
	Pit 163	CNA-48381.1	4387	39	S	4	
	Pit 129 (lyr. 1)	Beta-43235	4660	90	CH	2	Bernabeu (1993)
La Vital	Group 2	Beta-229792	4100	50	B	6	Pérez Jordà et al. (2011)
		Beta-229793	4150	50	B		
	Group 5 (SU 2202)	Beta-222445	4040	40	B	3	
	Group 8 (SU 3110)	Beta-222443	3830	40	HB	1	
Barranc del Migdia	II	Beta-300992	4070	30	HB	1	Soler Díaz et al. (2016)
	III/IV	Beta-296221	4020	30	HB	7	
Camí de Missena	Group (11/23/52/53)	Beta-508340	4150	30	B	2	This work
		CNA-50901.1	4148	32	B		
	Group (51/62)	Beta-331022	4050	30	B	3	Bernabeu et al. (2017b)
		Beta-331021	4030	30	B		
	Group (41/47/56/47)	Beta-331020	3800	30	B	3	
		Beta-508343	3810	30	B		This work
		Beta-508342	3890	30	B		
		Beta-569718	3900	30	B		
Niuet	Ditch A (lyr. 23/3)	Beta-527803	4460	30	B	2	
	Ditch A (lyr. 18/2)	Beta-527804	4410	30	B	4	
	Ditch A (lyr. 5/S)	Beta-527806	4170	30	B	9	
	Ditch A (lyr. 10/1)	Beta-527805	4200	30	B	5	
Quintaret	Pit 228 (SU 1161)	Beta-348076	4370	30	S	1	García Puchol et al. (2014)
Cova Randero	Burial context	Beta-396103	4130	30	HB	4	Soler Díaz et al. (2016)
		Beta-396104	4140	30	HB		
Cingle del Mas Cremat	Level II	Beta-232239	4129	49	S	2	Vizcaino León, 2010
Molinos de Papel	Burial 1	MAMS-11825	3699	30	HB	3	Lull Santiago et al. (2015)
Castillo de Frías Alb.	Level I	GrN-17550	3685	35	B	1	Harrison and Wainwright (1991)

S = seed (wheat or barley). HB = Human Bone. CH = Charcoal. B = Domestic fauna bone.

2011), group 41/46/47/56/57 from Camí de Missena (Bernabeu et al., 2017b; Pascual Beneyto, 2005), level 1 B from Castillo de Frías de Albarracín (Harrison et al., 1998; Harrison and Wainwright, 1991) and grave 1 (Lull Santiago et al., 2015) from Molinos de Papel (Pujante, 1999).

3.2. Archaeological sites for the predictive process

We have selected 31 archaeological contexts (Table 2) associated with 23 undated sites with arrowheads to explore the automatic Bayesian procedure. These sites correspond to habitation and burial caves and some open-air settlements and are briefly described:

Abric de l'Escurrupènia (Cocentaina, Alacant): this is a small rock shelter from to the Late Neolithic period. It has a total of 7 arrowheads associated with a collective burial (Pascual Benito, 1990).

Abrigo de Tóbar (Letur, Albacete): collective burial rock shelter of the Chalcolithic which presents a material culture very similar to that of neighboring areas, including five arrowheads (García Atienzar, 2010).

Barranc de Càfer 2 (Pedreguer, Alacant): this small cave has an altered stratigraphy covering Palaeolithic, Neolithic, and Chalcolithic periods (Soler Díaz et al., 2017). The available information on arrowheads is 22 remains, representing various types.

Barranc de Parra 3 (Pedreguer, Alacant): multiple burial cave and the available information (5 arrowheads) has no stratigraphic correspondence (Soler Díaz et al., 2017).

Camino del Molino (Caravaca de la Cruz, Murcia): collective burial cave with at least 1300 individuals (Lomba Maurandi and Haber Uriarte, 2016). It contains 51 arrowheads associated with the burials.

Campos (Cuevas de Almanzora, Almería): habitat site excavated in 1890 (Siret et al., 1980). The arrowheads were found in a house with other materials in which there are 47 arrowheads as well, comprising the five types defined in this work.

Casa Colorá (Elda, Alacant): burial cave with at least 3 burials and grave goods with 11 arrowheads ((Hernández Pérez, 1982; Jover Maestre and de Miguel Ibáñez, 2010) and ascribed to the Late Neolithic/Chalcolithic period.

Cova Ampla del Montgó (Xàbia, Alacant): cave excavated at the beginning of the 20th century, but the archaeological information used in this work, 3 arrowheads, comes from an altered archaeological context (Soler Díaz, 2007).

Cova de les Aranyes (Cocentaina, Alacant): corresponds to a small cave located in the karstic complex of the Serra d'Alberri. The arrowhead used in this work corresponds to the excavation of the funerary context carried out by the Centre d'Estudis Contestans and studied by Pascual Benito (1987).

Cova del Garrofer (Ontinyent, Alacant): the material analyzed comes from the publication by Bernabeu (1981) ascribed to the Late Neolithic/Chalcolithic period. Here we divide the arrowhead remains according to the different sectors defined during the excavation: sector K ($n = 6$), sector I-J ($n = 4$), sector S ($n = 3$) and, sector 3 ($n = 4$).

Cova del Negre (Cocentaina, Alacant): corresponds to another cave located in the Serra de l'Alberri whose information (35 arrowheads) comes from a clandestine intervention associated with multiple burials (Pascual Benito, 1987).

Cova del Petrolí (Cabanes, Castelló): it corresponds to a habitational cave with levels ranging from the Neolithic to the Bronze Age and the information used here comes from level II, assigned to the 4th/3rd millennium BC (Aguilella Arzo, 2002).

Cova dels Anells (Banyeres de Mariola, Alacant): the material analyzed derives from the review from the burial caves done by Soler Díaz (2002).

Table 2
Number of arrowhead types for each archaeological level used in the predictive approach. The information comes from the bibliographic review except those indicated in * that have been directly reviewed by one of the authors (JJP).

Site	Level	Arrows	Tp. 1	Tp. 2	Tp. 3	Tp. 4	Tp. 5	Tp. 6	Tp. 7
A. Escurrepènia	Burial	**7**	3	1	1	1		1	
A. Tóbar	Burial	**5**	1		2	2			
Barranc Càfer 2	Multiple	**22**	2		4	7	5	2	2
Barranc de Parra	Multiple	**5**		1			4		
Casa Colorá	Multiple	**11**	4		2	3			2
Camino del Molino	Burial	**51**	2		15	19	3		12
Campos	House	**47**	5		10	9	1		22
Cova Ampla Montgó	Mixed	**3**	2		1				
Cova Aranyes	Burial	**1**							1
Cova del Garrofer	3	**4**	1			1			2
	I-J	**4**	1		1	1			1
	K	**6**	1		1	2			2
	S3	**3**	1		2				
Cova del Negre	Burial	**25**			2	2		1	20
Cova del Petrolí	I/II	**1**			1				
Cova dels Anells	Burial	**19**	5		5		2	1	6
Cova d'en Pardo	III	**20**	10	4				4	2
Cova Santa Vallada	A	**5**				3		2	
	B	**3**			2	1			
Cueva Sagrada	Burial	**6**	2		4				
Ereta del Pedregal	I	**36**	7	25	3	1			
	II	**27**	4	17		4			2
	III	**23**	3	2	10	5			3
	IV	**41**	10	1	2	14			14
Font de Mahiques *	Unic	**5**	1	1	2	1			
La Torreta	SU 2	**2**	1		1				
	SU 1	**8**	1		3	1			3
Muviedro	Burial	**37**		2	3	25			8
Niuet	Pit 3	**4**	1		2				
Puntal Rambla Castellarda *		**41**	3	1	3	2		1	31
Sima de la Pedrera	Burial	**5**		3					2

In this cave, 19 arrowheads were recovered.

Cova d'en Pardo (Planes de la Baronia, Alacant): this site is one of the best-studied in terms of the phenomenon of multiple burials (Soler Díaz, 2012, 1999; Soler Díaz and Roca de Togores Muñoz, 1999). The information used in this work comes from level III and a total of 20 arrowheads have been documented (Soler Díaz, 2002).

Cova Santa (Vallada, València): this cave has three sectors. C refers to chronologies of Iberian culture and medieval period. The information used in this work comes from the two funerary sectors (A & B) defined during the excavation (Martí Oliver, 1981) and dated during the Bell-Beaker period. Therefore, we will use each sector as a unit of analysis following the information provided by Martí.

Cueva Sagrada (Lorca, Murcia): individual burial in cave with very well-preserved grave goods including a complete conserved dress and a straw carpet. It also contained 6 arrowheads (Ayala Juan, 1987).

Ereta del Pedregal (Navarrés, València): the collection of arrowheads of this open-air site is enormous and one of the most important from Late Neolithic and Chalcolithic periods in Mediterranean Spain. The archaeological information (Juan Cabanilles, 2008) has been organized in four phases according to the stratigraphy defined by Juan Cabanilles (1994). The first phase corresponds to Ereta I, followed by Ereta II and Ereta III, and finally, the last phase of the archaeological deposit corresponds to Ereta IV.

Font de Mahiques (Quatretonda, València): an open-air site characterized by the presence of negative structures (silos). The information used comes from the study of the arrowheads recovered in Marti's excavation (Fletcher, 1982).

La Torreta (Elda, Alacant): this corresponds to an open-air in which numerous pits and silos have been documented, as well as a ditch (Jover Maestre et al., 2010). The information used in this work comes from the SU-1 and SU-2 of the ditch. Stratigraphic unit 2 has a^{14}C made on a fragment of *pinus halepensis* that places it at the end of the 4th millennium B.C.

Murviedro 1 (Lorca, Murcia): collective burial inside a megalithic structure almost destroyed. The archaeological information used here, 37 arrowheads, comes from this altered context (Ibañez Sánchez, 1985).

Niuet (Alqueria d'Asnar, Alacant): an open-air site characterized by the presence of negative structures (silos) and defensive ditch (Bernabeu et al., 1994). The information used comes from the silo 5.

Puntal de la Rambla Castellarda (Llíria, València): the information used in this works comes from the archaeological excavation carried out during the 1970s by Aparicio in this open-air site with remains of stone walls dated around the transition from the 4th millennium to the 3rd (Aparicio Pérez et al., 1977). The information used comes from the study of the arrowheads recovered in Aparicio's excavation.

Sima de la Pedrera (Benicull del Xúquer, València): this corresponds to a multiple burial in a cave typical of the 3rd millennium (Bell-Beaker period). The total number of arrowheads recovered during the archaeological intervention amounts was 5 (Aparicio Pérez, 1978).

3.3. Bayesian classification process

The method used in this work is an automatic Bayesian method very useful and popular in text classification (Wang et al., 2013). The potentiality of this approach in archaeology has been recently explored in Armero et al. (2021). This procedure is structured in two stages. The first step aims at learning about the distribution of the proportion of arrow types in each of the chronological periods considered. It is an inferential process based on the Bayesian Dirichlet-multinomial inferential process (Alvares et al., 2018) that uses the information provided by the sites with a known accurate chronology. The second step is predictive. It involves calculating the posterior predictive distribution of the chronological period to which an undated archaeological assemblage belongs in which a certain number of arrows of each type has been found. This predictive distribution combines the information of the number and types of arrowheads found in this new assemblage and the knowledge of the proportion of arrow types in each chronological period acquired in the first stage. The basic Bayesian model that we use in this paper is taken from Armero et al. (2021). In this paper we include as a statistical novelty a model checking section with a sensitivity analysis of the posterior distribution with respect to different prior distributions and a cross-validation subsection based on the predicted a posteriori distribution.

3.3.1. Dirichlet-multinomial inferential process

To carry out the Bayesian learning process, we have considered a probabilistic sampling multinomial model for the number of arrowheads $\boldsymbol{y}_i = (y_{i1}, \ldots, y_{iJ})$ in period i, where y_{ij} is the number of arrowheads of type j in that period, with parametric vector $\boldsymbol{\theta}_i = (\theta_{i1}, \ldots, \theta_{iJ})$, where θ_{ij} is the probability that an arrowhead of period i is of type j. In general, we assume that index i is for period and ranges in {1,2, …, I} (where I is the number of periods covered) and, similarly, index j is for arrowhead's type and varies in {1,2, …, J} (J is the number of different arrowheads). In our study the number of periods is $I = 5$ and the number of different types of arrowheads is $J = 7$.

For each period i, this approach assumes an inferential process for each $\boldsymbol{\theta}_i$ that will begin by selecting a non-informative distribution $\pi(\boldsymbol{\theta}_i)$ for the probabilities in $\boldsymbol{\theta}_i$ which will be updated using the collected data information.

In the specialized literature, there have been certain debate regarding which is the appropriate non-informative prior for the parameters of the multinomial distribution. Among the proposals, special mention deserves Haldane's prior (1948), Perks' prior (1947), hierarchical approach (Berger et al., 2015), Jeffreys' prior (1946) and Bayes-Laplace prior (Kabán, 2007). They are all prior Dirichlet distributions, denoted Di $(\boldsymbol{\theta}_i|\mathbf{a}_0)$, with different values of the parameters vector $\mathbf{a}_0 = (a_0, a_0, \ldots, a_0)$ (Table 3).

Although all these proposals present good theoretical properties it is worth explaining that the use of the Haldane distribution requires that all the categories considered will be observed in the data. Otherwise, the resulting a posteriori distribution is improper and we will not be able to continue the inferential process properly.

The Dirichlet distribution is conjugate to the multinomial model, and for this reason the subsequent posterior distribution is also a Dirichlet distribution as follows.

$$\pi(\boldsymbol{\theta}_i|\boldsymbol{y}_i) = \mathrm{Di}(\boldsymbol{\theta}_i|a_{i1} = y_{i1} + a_{01}, a_{i2} = y_{i2} + a_{02}, \ldots, a_{iJ} = y_{iJ} + a_{0J}). \tag{1}$$

The posterior marginal distribution for the abundance of arrowheads type j in period i is the beta distribution Be $(a_{ij}, a_{i+} - a_{ij})$, where $a_{i+} = \sum_{j=1}^{J} a_{ij}$.

In this study, we use the Perks' distribution following Alvares et al. (2018) recommendations. In Subsection 4 devoted to model checking, we have carried out a sensitivity analysis of the inferential process regarding the non-informative prior distributions discussed above.

Table 3
Non-informative Dirichlet prior distributions. J refers to the number of defined arrowhead types.

Prior distribution	$\pi(\theta_i) = \mathrm{Di}\ (\theta_i\|\mathbf{a}_0)$ with:
Bayes-Laplace	$\mathbf{a}_0=(1,1, \ldots,1)$
Haldane	$\mathbf{a}_0=(0,0, \ldots,0)$
Hierarchical	$\mathbf{a}_0=(\sqrt{2}/J, \sqrt{2}/J, \ldots, \sqrt{2}/J)$
Jeffreys	$\mathbf{a}_0=(1/2,1/2, \ldots,1/2)$
Perks	$\mathbf{a}_0=(1/J,1/J, \ldots,1/J)$

3.3.2. Predictive approach

In the first phase of the Bayesian model described above, we have estimated the probabilities associated to the different arrow types considered for each period via posterior Dirichlet distribution. In the second phase, we derive the posterior predictive distribution that assigns to an undated site the period it belongs, say m^*. This assignment is conditional on the abundance of each type of arrowheads $\boldsymbol{y}^* = (y_1^*, \ldots, y_J^*)$ found in that new site m^* and the information from the previous inferential process $\boldsymbol{y}$, and comes in the form of a probabilistic distribution over the possible periods.

In application of Bayes' theorem (formula 2), this distribution is

$$P(m^* = i|\boldsymbol{y}^*, \boldsymbol{y}) = C\, P(\boldsymbol{Y}^* = \boldsymbol{y}^*|m^* = i, \boldsymbol{y})P(m^* = i|\boldsymbol{y}),\ i = 1, \ldots, I, \tag{2}$$

where C is the normalizing constant that makes this distribution to sum one and $\boldsymbol{y}$ represents all the data of the inferential process. Apart from C, the first term above is obtained integrating the posterior distribution of θ_{ij}(Armero et al.,2021). Given the conjugacy of the prior used, it can be easily seen that (formula 3)

$$P(\boldsymbol{Y}^* = \boldsymbol{y}^*|m^* = i, \boldsymbol{y}) = \frac{n^*!}{\prod_{j=1}^{J} y_j^*} \frac{\Gamma\left(\sum_{j=1}^{J} a_{ij}\right)}{\prod_{j=1}^{J} \Gamma(a_{ij})} \frac{\prod_{j=1}^{J} \Gamma\left(a_{ij} + y_j^*\right)}{\Gamma\left(\sum_{j=1}^{J} (a_{ij} + y_j^*)\right)} \tag{3}$$

where $n^* = \sum_{j=1}^{J} y_j^*$ and $\Gamma(.)$ denotes the gamma function. Finally, the last term, $P(m^* = i|\boldsymbol{y})$ is the probability that the undated site belongs to period i given that no information of arrowheads on the site is available. Since here only the data from the estimation step can be used, we estimate (formula 4) this probability (Barber, 2012) simply as the proportion of sites from period i out of the total number N of sites sampled.

$$P(m^* = i\boldsymbol{y}) = \frac{n_i}{N}, \tag{4}$$

where n_i indicates the number of sites from period i.

4. Results and discussion

To enable reproducibility and transparency (Marwick, 2017) R code and original datasets are available in Zenodo repository (see Pardo-Gordó and Armero, 2021). All calculations have been done with R statistical software version 4.1 (Core Team, 2021) and graphical representations have been done with the *ggplot* library (Wickham, 2016).

4.1. Estimation process

Data from the sites of the different periods in the study are presented in Table 4 regarding the number of arrowheads of each type.

The posterior distribution for the abundance of each type of arrowhead in each period is computed from formula 1 and data in Table 4. Fig. 3 shows the posterior marginal distribution of the abundance of the several arrowhead types in each of the five chronological phases

Table 4
Number of arrows of each type in each of the time periods of the study.

Period	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Total
1	2	3	1	0	0	0	0	*6*
2	4	5	2	1	0	0	0	*12*
3	6	0	8	9	4	0	10	*37*
4	2	0	2	1	2	0	6	*13*
5	1	0	0	2	0	1	9	*13*
Total	*15*	*8*	*13*	*13*	*6*	*1*	*25*	*81*

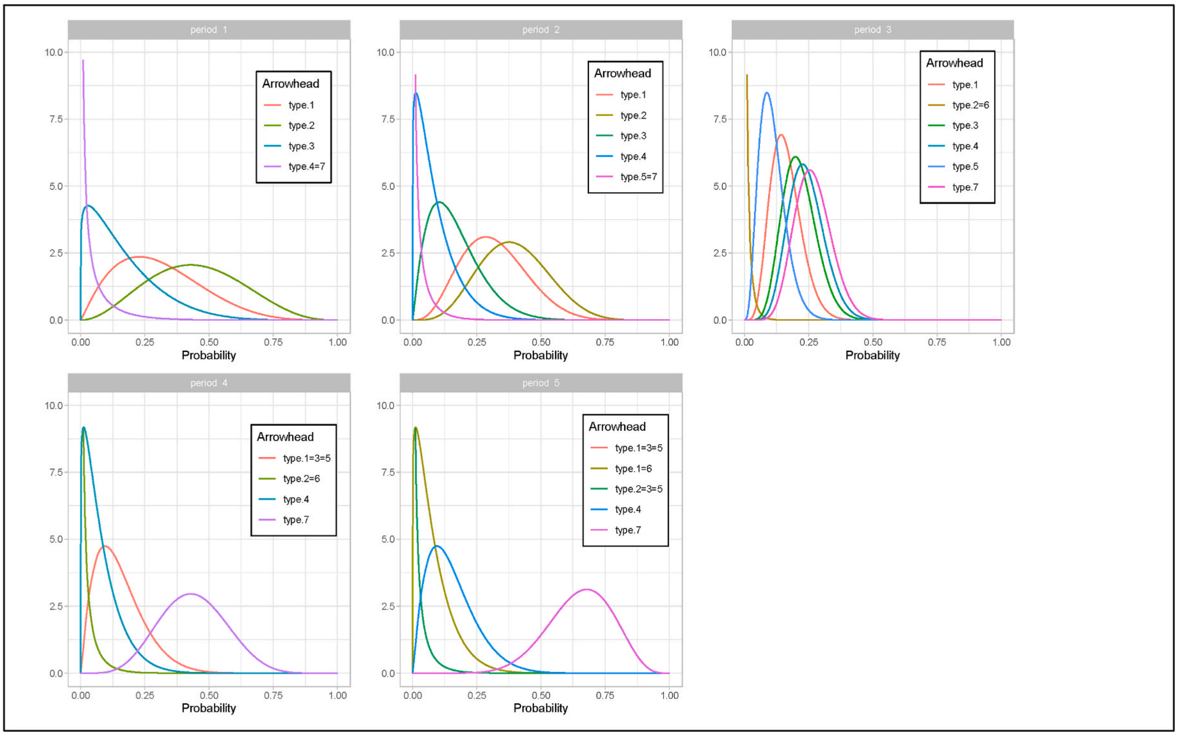

Fig. 3. Posterior marginal distributions for the probability associated with each type of arrowhead in each period based on Perk's prior distribution. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

considered in this work.

Period 1 (3600–3064 cal. BC) and period 2 (3290–2839 cal. BC) show similar patterns characterized by a high probability occurrence for type 1, type 2 and, to a lesser extent, type 3. The remaining types (4–7) have very low probabilities.

Period 3 (2945–2522 cal. BC) shows similar probabilities of occurrence for types 1, 3, 4, 5 and 7 but types 4 and 7 have a slightly higher presence. On the other hand, the remaining types (type 2 and type 6) are probabilistically irrelevant.

In period 4 (2634–2351 cal. BC), type 7 has the most probability occurrence and, to a lesser extent, type 1, 3 and type 5. Lastly, type 2 and type 6 are practically absent.

Finally, period 5 (2472–2000 cal. BC) is characterized by a high probability occurrence of type 7 (close to 75%) followed by arrowheads type 4. The presence of all other types of arrows is basically irrelevant except for type 6 arrows which have a small probability of occurrence.

4.2. Prediction process

Once the learning phase was completed, an automatic process was carried out to assign those sites that are not dated to their corresponding chronological phase. We have obtained the posterior predictive distribution, expressed in formula 2, for some non-dated archaeological contexts. Results are plotted in Fig. 4 where several patterns can be identified.

i) Pattern 1. This is a unimodal pattern where the predictive distribution of the subsequent site is concentrated in only a period with a probability greater than 0.75. Within this category there are the archaeological sites of Abric d'Escurrupènia, Abrigo de Tóbar, Barranc de Cáfer, Camino del Molino, Campos, Casa Colorá, Cova d'en Pardo, Cova del Negre, Cova del Garrofer (K and S3), Cova Santa A and B, Ereta del Pedregal I, Ereta del Pedregal II and III, Font de Mahiques, Rambla Castellarda and Torreta 1.

ii) Pattern 2. Corresponds to sites in which the predictive distribution is mostly concentrated in two periods with a joint probability greater than 0.75. The sites of Barranc de Parra 3, Cova dels Anells, Ereta IV, Cova del Garrofer I-J and Muviedro 1 lie in this category.

iii) Pattern 3. These are lithic assemblages with predictive probabilities basically concentrated in three chronological moments. Within this category we can find the archaeological sites of Cova Ampla del Montgó, Cova de les Aranyes, Cova del Petrolí, Cueva Sagrada, Niuet (silo-5), Sima de la Pedrera and Torreta 2.

The results obtained show a high concordance with the nature of each assemblage, that are sites/levels with or without stratigraphy (Table 5).

Focusing on those levels with stratigraphical relationship, the results of the posterior predictive distribution show stratigraphic coherence. For example, the observed results of Cova Santa not only display its stratigraphic relationship (level B is older than level A), but also posterior predictive outputs are in line with the subsequent expectations based on our previous knowledge (see Table 5). In this sense, level B is interesting, which according to the archaeological information is situated in period 3–4. However, based on the predictive approach, it indicates that it should be in period 3 thus reducing the chronological duration of this level. This outcome is consistent not only for the typology of the arrowheads themselves but also for the presence of other diagnostic elements such as metal and the absence of bell-beaker pots. The same behavior may be noted on the other sites with stratigraphic relation as Ereta del Pedregal and Torreta.

The observed results of Casa Colorá and Cova del Garrofer (S3) are reliable, which both the expected results and the predictive approach fall in period 3. The same pattern is observed in Cova Santa (level A), where expected and predicted results place in phase 5. Likewise, as we have seen above, the predictive approach sometimes reduces the chronological span defined in the expected observation. The reduction of temporal uncertainty can be observed in Barranc de Cáfer 2, Campos,

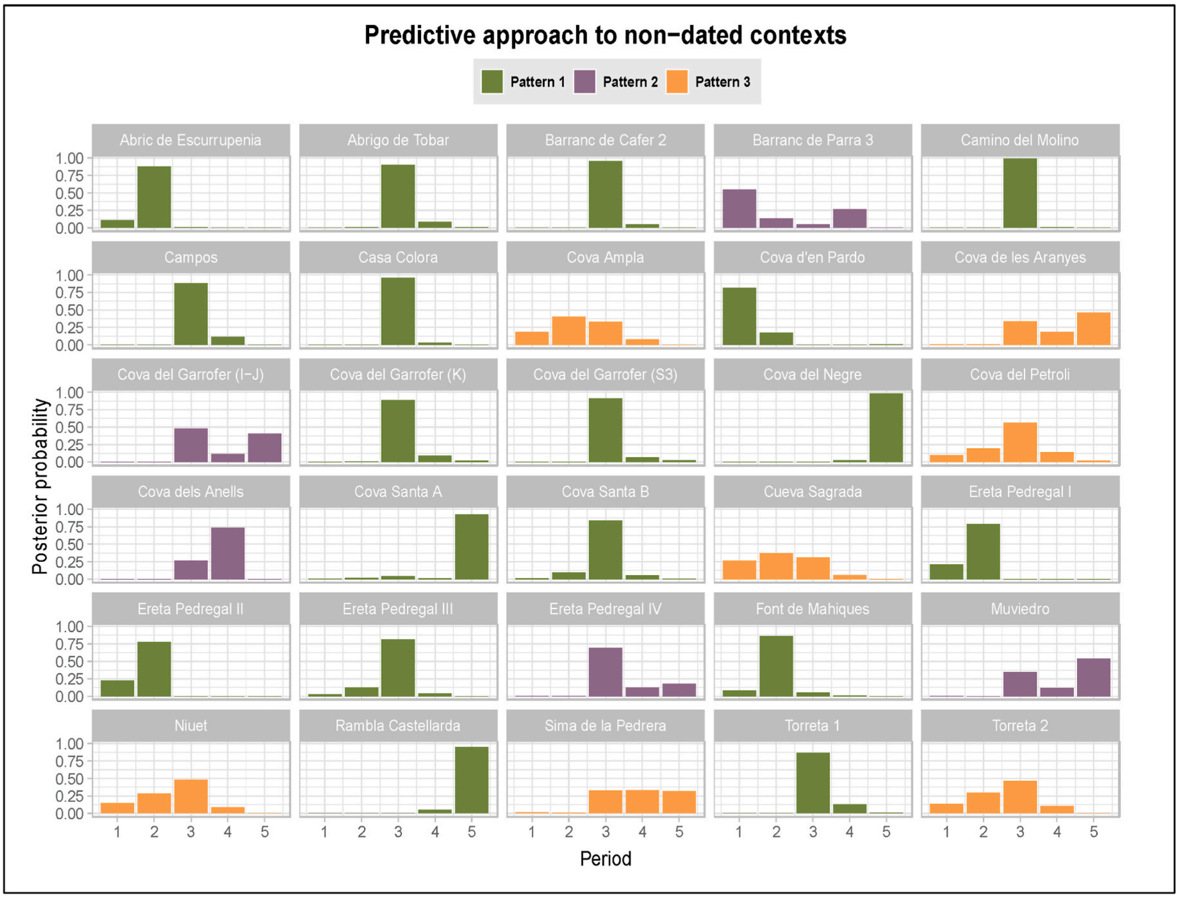

Fig. 4. Posterior marginal distribution for the probability associated with each type of arrowhead in each period. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 5
Archaeological levels with stratigraphical relations. Expected results are the chronology expected based on cultural information and observed results are the periods obtained after the predictive approach.

Site	Stratigraphic relation	Expected	Observed
Abric d'Escurrupènia		1	2
Abrigo de Tóbar		1–2	3
Barranc de Cáfer 2	Palimpsest	2–3	3
Barranc de Parra 3		2–3	1, 3-4
Camino del Molino		Altered	3
Campos		2–4	3
Casa Colorá		3	3
Cova Ampla	Palimpsest	Altered	1–3
Cova Aranyes		3–4	3–5
Cova d'en Pardo		2	1
Cova del Negre		3–5	5
Cova del Petrolí		3–4	2–3
Cova dels Anells		3–4	3–4
Cova Garrofer I/J		3	3–5
Cova Garrofer K		2–3	3
Cova Garrofer S3		3	3
Cova Santa A	Post Cova Santa B	5	5
Cova Santa B	Prior Cova Santa A	3–4	3
Cueva Sagrada		1–2	1–3
Ereta Pedregal I		1	1–2
Ereta Pedregal II	Post Ereta Pedregal I	2	1–2
Ereta Pedregal III	Post Ereta Pedregal II	3–5	3
Ereta Pedregal IV	Post Ereta Pedregal III	3–5	3
Font de Mahiques		1	2
Muviedro 1		2–4	3–5
Niuet		1–2	1–3
Rambla Castellarda		2–5	5
Sima de la Pedrera		4–5	3–5
Torreta 1	Post to Torreta 2	2–3	3
Torreta 2	Prior to Torreta 1	2–3	2–3

Cova del Negre, Cova del Garrofer (level K), Cova Santa B, Rambla Castellarda and Torreta 1 where predictive results place these sites in one specific period.

It should also be noted that when we use a site characterized by mixed/altered stratigraphy (palimpsest) we cannot define a specific period based on archaeological remains, hence we make a general assumption. However, when we have applied our Bayesian procedure to this type of assemblages, we obtain a specific range of chronological duration for the site (Cova Ampla del Montgó) or a specific period (Camino del Molino).

Finally, there are some assemblages explored in this work in which the predictive outputs are divergent from the expected results. In the case of Cova d'en Pardo according to lithic remains we place its chronology in period 2. Other sites such as Abric d'Escurrupència and Font de Mahiques in which the expected results place both in period 1, the predictive distribution places them in phase 2. In addition, some sites such as Barranc de Parra and Cova del Garrofer (I-J) the posterior predictive distribution results indicate a great uncertainty.

These discrepancies can be explained by the persistence of certain types of arrowheads throughout the entire sequence analyzed, as is the case of the peduncle arrowheads. Other issues to consider are the individual life history of the arrowheads themselves, such as reworking effects and fractures generated during impacts (Bettinger et al., 1991; Flenniken and Raymond, 1986; Loendorf et al., 2019; Wilke and Flenniken, 1991).

To supply these small inconsistencies between expected and predicted results the incorporation of other complementary diagnostic archaeological covariates to our Bayesian procedure like the presence of metal elements and bell-beaker ceramics may help to establish a more precise chronology.

4.3. Model checking

The validation of the model used to analyze the data of a study is an important element of any statistical analysis because the results obtained from it depend on the model's ability to explain the reality of the problem. The Bayesian literature on the subject is extensive and includes many different proposals (Dey and Rao, 2005). We adopt the recommendations of Box (1980) and will treat model validation through prediction, according to the cross-validated predictive density (Gelfand et al., 1992), rather than estimation. Moreover, the prior distribution is part of the Bayesian model. In this regard, we also conduct a sensitivity analysis to assess the influence of the different non-informative prior distribution proposals above on the posterior estimation.

4.3.1. Sensitivity analysis

The Haldane and the hierarchical prior are not included in this part. In most of the sites in our sample not all types of arrows are observed, so that with the Haldane prior we would have parameters with 0 values in the corresponding posterior distribution, which would make it probabilistically inappropriate and impossible to work with. On the other hand, the hierarchical distribution is very similar to Perk's prior and therefore we expect both to generate similar results.

Fig. 5 shows the posterior marginal distribution of the abundance of the several arrowhead types in each of the five chronological phases considered obtained from Bayes-Laplace, Jeffreys's and Perk's prior distributions.

If we look at the graphs in Fig. 5, we find hardly any differences between the posterior distributions of arrow types in the different

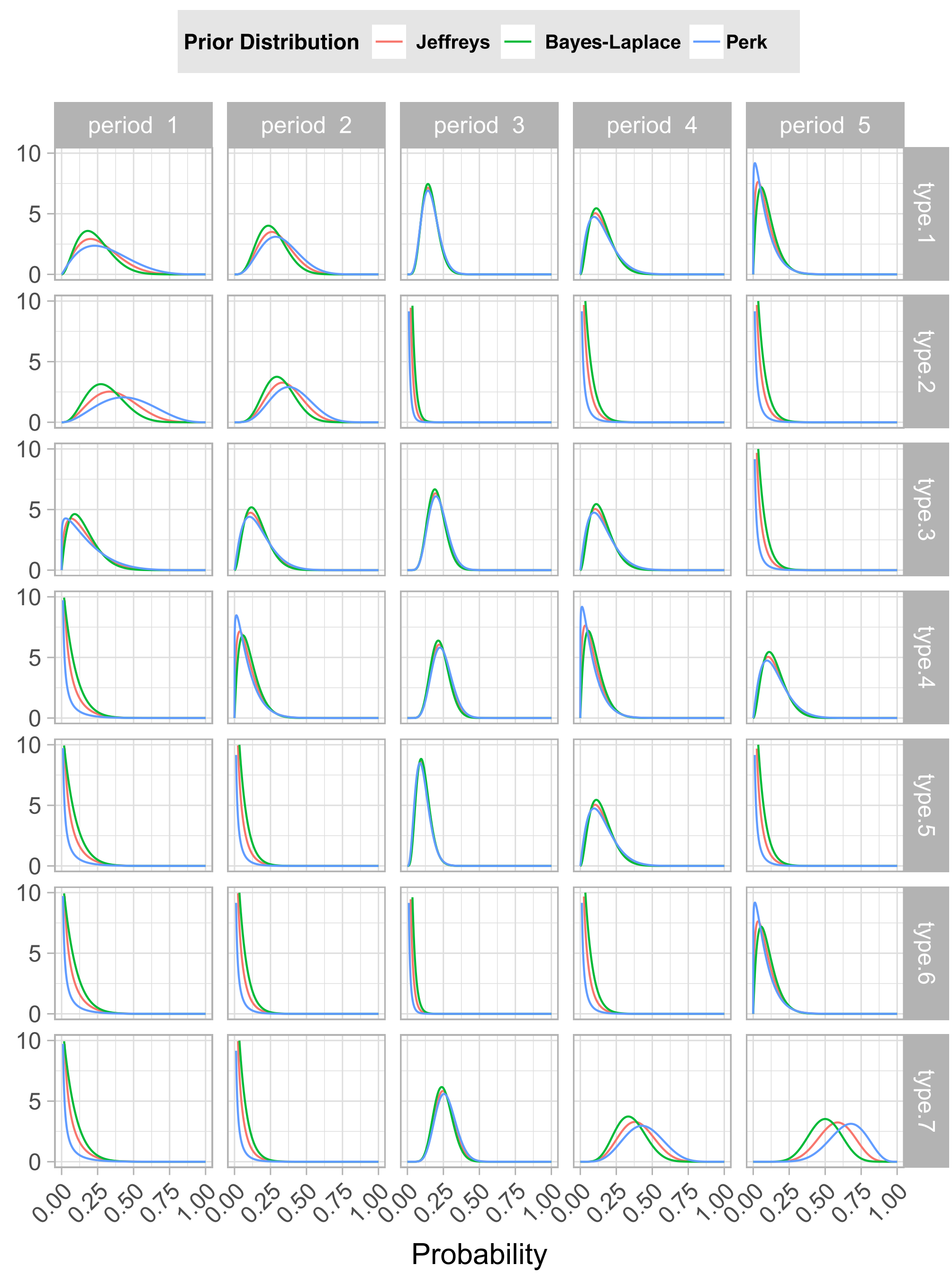

Fig. 5. Posterior marginal distribution for the probability associated with each type of arrowhead in each period based on Bayes-Laplace, Jeffreys and Perk prior distributions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

periods. The most homogeneous situation corresponds to period 3 in which the highest number of arrows, 37, has been collected. Since the posterior distribution combines the prior and the experimental information, in this case, with 37 data, the influence of the prior is blurred. The opposite is the scenario in period 1, where only 6 arrowheads were collected.

For period 1, the mean of the probabilities obtained from the Bayes-Laplace, Jeffreys and Perk prior distributions are, respectively, 0.23, 026 and 0.31 for type 1 arrowheads; 0.31, 0.37 and 0.45 for type 2 arrowheads; and 0.15, 0.16 and 0.16 for type 3 arrowheads. For arrowheads type 4, 5, 6 and 7, which have not been observed in the sites of this period, posterior probabilities are 0.08 (Bayes-Laplace), 0.05 (Jeffreys) and 0.02 (Perk). The Perk prior distribution yields smaller probability values (0.02) for arrowhead types that do not appear in the sample compared to those obtained from the Jeffreys prior (0.05) and the Bayes-Laplace prior (0.08), and higher values for the more prevalent arrowhead types.

In the case of period 3, the values obtained with the three prior distributions are very similar. The most abundant type of arrowheads in this period is type 7, of which 10 artefacts have been found. The mean probability assigned to this type of arrowhead is 0.25 when using the Bayes-Laplace prior, 0.26 with Jeffreys' prior and 0.27 with Perk's prior. For the two types of arrowheads absent in this period, type 2 and type 6, the observed values are small and very similar 0.023 with the Bayes-Laplace prior, 0.012 with the Bayes-Laplace prior, and 0.004 with the Perk prior. The three prior distributions estimate the same probability, 0.16 and 0.11, for the abundance of type 1 and type 5 arrowheads, respectively. With the Bayes-Laplace, Jeffreys and Perk distributions we obtain the probabilities 0.20, 0.21, and 0.21 for type 3 arrowheads, and 0.23, 0.23 and 0.24 for type 4 arrowheads, respectively.

4.3.2. Model validation

We have applied the cross-validated predictive density to several sites with radiocarbon information that have not been used in the learning phase. In this sense, we have selected 5 archaeological contexts (Table 6) with arrowheads related to four dated contexts that are briefly described below.

Fuente Isso (Hellín, Albacete): it is an open-air site characterised by the presence of negative structures (silos), a ditch and a habitat structure. The cultural and radiometric information comes from the restructuring of the interior space of the house (García Atienzar, 2010).

Las Churuletas *(Purchena, Almería)*: this site is part of the so-called '*purchena group*', which corresponds to the first evidence of megalithism in the Iberian southeast (Aranda Jiménez et al., 2018). The cultural information used here comes from tomb 1 (De la Peña y Montes de Oca, 1986).

Llano del Jautón *(Purchena, Almería)*: this is another site from the '*purchena group*' (Aranda Jiménez et al., 2017). Its cultural information, tomb 1, comes from the revision made by Acosta and Cruz-Auñón (1981).

Vilches IV (Hellín, Albacete): this is an open-air site with evidence of three domestic structures (García Atienzar and Jover Maestre, 2021). The information used in this paper comes from house 2 and house 3 because they contain radiometric and cultural information.

Fig. 6 shows the predicted distribution of the period to which each of the sites belongs according to radiocarbon dating procedures and to the predictive distribution generated by our classification procedure. These outputs can be grouped in three patterns.

i) the period with highest predicted probability (more than 0.45) and the estimated radiocarbon calibrated date at 95% provides the same chronological phase. Sites of Las Churuletas (tomb 1), Vilches IV (house 2) and Llanos del Jautón correspond to this category.
ii) the calibrated date covers more than one chronological phase and the period with maximum predicted probability (0.43) falls in these phases. The site of Vilches IV (house 3) correspond to this category.
iii) Sites where the maximum posterior predictive distribution falls outside of the maximum radiocarbon probability. There, we have the site of Fuente Isso.

In general, the predicted probabilities associated to each period agree with the radiocarbon information. There is a case where the result of the posterior predictive distribution does not perfectly fit the radiometric data (Fuente Isso). The reason is that this archaeological context is defined as a restructuring of space, hence this could imply that the ^{14}C was affected by some post-depositional process (García Atienzar, 2010, p. 45). In this sense, the prediction obtained from the Bayesian procedure (period 3) is more accurate that the available radiocarbon information (period 1 to 3).

Another issue to consider is that the archaeological contexts used for validation present a reduced corpus of arrowhead. Then, can the number of flint bifacial arrowheads for site assemblage affect our predictive results? We must reiterate that the predictive assignment is conditional on the abundance of each type of arrowhead found. Therefore, we can conclude that the predictive results are reliable and have high chronological consistency.

Table 6
Archaeological levels and radiocarbon dates used for model validation. * Indicates ^{14}C that are not equal after applied the Ward and Wilson (1978).

Site	Level	Id-^{14}C	BP	±	Sample	Arrows	Reference
Fuente Isso	House	Beta-221996	4400	50	B	5	García Atienzar, 2010
Las Churuletas	Tomb 1	Beta-439073	4200	30	HB	2	Aranda Jiménez et al., 2017
Llano del Jautón	Tomb 1	ETH-74314	4175	20	HB	4	Aranda Jiménez et al., 2017
		ETH-74313	4164	20	HB		
		ETH-74312	4163	20	HB		
		ETH-74318	4153	20	HB		
		ETH-74317	4151	20	HB		
		ETH-74315	4148	20	HB		
		ETH-74316	4112	20	HB		
Vilches IV	House 2	Beta-454433	3910	30	B	1	García Atienzar and Jover Maestre, 2021
	House 2	Beta-397980	3930	30	B		
	House 3	Beta-450082*	3880	30	WB	4	
	House 3	Beta-397981*	4150	30	B		

S = seed (wheat-barley). HB = Human Bone. CH = Charcoal. B = Domestic fauna bone. WB = Wild fauna bone.

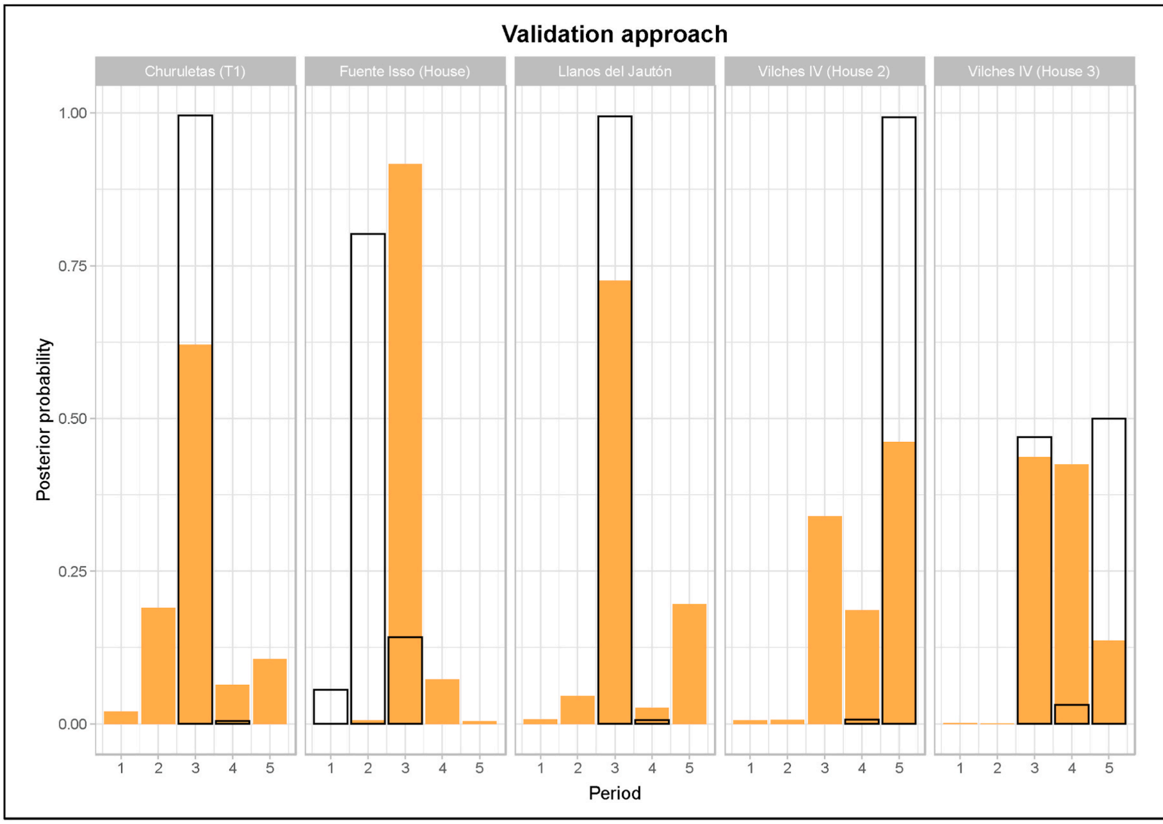

Fig. 6. Posterior marginal distributions for the probability associated with each type of arrowhead in each period. The filled column refers to the Bayesian predictive probability while the unfilled column refers to the radiocarbon probability distribution. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

5. Conclusions

An important issue un archaeological dating is how to process cultural findings to provide an estimate (with an associated uncertainty) of the (pre)historic period during which a site was dwelt. In this paper we propose a Bayesian classification method to approach this problem using the configuration of arrowhead types collected in a site. The procedure is based on a learning probabilistic formula based on an objective prior distribution. The prior conjugates with the statistical model assumed hence leading to straightforward and automatic classification methods that do not rely on sophisticated numerical techniques like simulation-based approximations.

We have applied the methodology with very positive conclusions. In summary, we obtain predicted chronologies that are highly consistent with the available context-based information (i.e., stratigraphy) and furthermore, are clearly aligned with radiocarbon dating as we show in Section 4.3.2 (Model Validation).

Purely from the point of view of the underlying statistical techniques there could be some genuine concerns that have to be with i) the choice of the prior distribution and ii) the suitability of certain assumptions that shape the probabilistic model adopted. Regarding i) we acknowledge that there are alternatives in the specialized literature to Perk prior (the one we use and ultimately suggest). Nevertheless, except in marginal situations with extremely limited sampling information, the proposed dating methodology behaves satisfactorily exhibiting a robust behavior with respect to the prior adopted as shown in Section 4.3.1. With respect to concern ii) above, our model is purposedly simple enough as to allow a subsequent straightforward methodology. A particularly useful simplification has been treating the arrowheads configuration in different sites in an aggregated way. As a referee has suggested, a more realistic model could have a hierarchical structure to which each site would contribute individually. In the context of Bayesian classification, such type of strategies has been successfully applied in social sciences (see Congdon, 2006). While we certainly agree, the scarceness of the type of context information used (sites with very few arrowhead findings) makes unfeasible such modelling refinement but clearly see the potential of such hierarchical model in combination with cultural material that is more abundant like for instance ceramic remains. Finally, and returning to our problem, the closeness of the sites considered (see Fig. 1), several of which even correspond to different levels of the same place, plays clearly in favor of the reliability of the "aggregated" strategy.

Declaration the competing interest

Conceptualization: SPG, JBA, JJP, CA and GGD; Methodology: SPG, JBA, JJP, CA and GGD.; Data analyses and R code: SPG and CA; Data: JJP, JBA and SPG; Writing/review and editing, SPG, JBA, JJP, CA and GGD.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2022.105555.

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