Bayesian classification for dating archaeological sites via projectile points

Carmen Armero[1], Gonzalo García-Donato[2], Joaquín Jiménez-Puerto[3], Salvador Pardo-Gordó[3] and Joan Bernabeu[3]

Abstract

Dating is a key element for archaeologists. We propose a Bayesian approach to provide chronology to sites that have neither radiocarbon dating nor clear stratigraphy and whose only information comes from lithic arrowheads. This classifier is based on the Dirichlet-multinomial inferential process and posterior predictive distributions. The procedure is applied to predict the period of a set of undated sites located in the east of the Iberian Peninsula during the 4th and 3rd millennium cal BC.

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1 Introduction

Dating is a key element for archaeologists. A time scale to locate the information collected from excavations and field work is always necessary in order to build, albeit with uncertainty, our most remote past. Archaeological scientists generally use stratigraphic expert information and dating techniques for examining the age of the relevant artifacts. Bayesian inference is commonly used in archaeology as a tool to construct robust chronological models based on information from scientific data as well as expert knowledge (e.g. stratigraphy) (Buck, Cavanagh and Litton, 1996).

Radiocarbon dating is one of the most popular techniques for obtaining data due to carbon's presence in any being that has lived on Earth. However, it is not always possible in all studies to collect organic material and obtain that type of information or to have good stratigraphic references. In these cases, the challenge is to be able to assign non

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[1] Departament d'Estadística i IO. Universitat de València, Carrer Doctor Moliner 50, 46100, Burjassot, Spain.

[2] Department of Economics and Finance. Universidad Castilla-La Mancha. Edificio Jurídico-Empresarial "Melchor de Macanaz", Plaza de la Universidad, 1, 02071 Albacete, Spain.

[3] Department of Prehistory, Archaeology and Ancient History, Universitat de València, Avda. Blasco Ibáñez 28, 46010 València, Spain.

radiocarbon dated collections to specific chronological times. The relevant information is based on cultural material that includes elements with markers that point out the different cultural traits of the social groups involved as well as the social relationships between them. One of these useful items is the lithic productions, and more specifically the arrowheads.

During the 4th and 3rd millennium cal BC bifacial flint arrowheads appear and spread in the east of the Iberian Peninsula. Archaeological research suggests that the shape of these arrowheads could be related with specific period and/or geographical social units spatially defined.

In this context, we propose an automatic Bayesian procedure, very popular in text classification (Wang, Hodges and Tang, 2003), based on predictive probability distributions for classifying the period to which an undated site belongs according to the type and number of arrows found in it. This proposal takes into account the Dirichlet-multinomial inferential process for learning about the proportion of different types of arrowheads in each chronological period, and the concept of posterior predictive distribution for a new undated site.

This paper is organized in five sections. Following this introduction, Section 2 briefly introduces the archaeological framework and the lithic material that will be the basis for the classification process. Section 3 describes the two stages of the Bayesian statistical analysis. The first is of an inferential type and focuses on the study of the abundance of different types of arrows in the different periods considered. The second uses the information from the first stage to predict the period of an undated site from the number and type of arrowheads encountered. Section 4 applies the methodological procedure from the previous section to a set of sites in the east of the Iberian Peninsula during Late Neolithic and Chalcolithic (4th-3rd millennium BC). Finally, Section 5 concludes.

2 Chronological periods and lithic information

One of the main goals in archaeological research is focused on the way the members of the prehistoric cultures interact with the landscape and the objects. From an evolutive perspective, the way human cultures change through space-time is determined by inheritance patterns, adaptation and interaction (Shennan, Crema, and Kerig, 2015). Therefore, the analysis of items from the archaeological records, able to capture the cultural evolution of the human groups, would be a main goal for the researcher.

The concept of "culture" covers many factors. Hence, we will use the material culture as an archaeologic proxy in order to analyse the evolution and dispersion of the cultural traits in the study area. Not all the items included in material culture are useful for that. Those which show a wide geographic and cultural dispersion or whose variability is low are not convenient to detect changes. This is not the case with lithic productions, and more specifically arrowheads, which provide information not only for understanding

the socio-economic and cultural structures of human groups, but they can be used as a valuable tool for chronological dating.

The arrival of the neolithic economy, based on domestic resources, in the Iberian Peninsula is dated on the first half of the 6th millennium cal BC. We will have to wait until the 4th-3rd millennium to be able to witness clear winds of change. This is the moment of the appearance of a higher level of hierarchy in some societies. The Late Neolithic (4th-3rd millennium cal BC) in the oriental Iberian façade is the time of the transit to a higher complexity in social and economic terms. This process will last long and it will crystallize by the end of the 3rd millenium cal BC (Bernabeu and Orozco, 2014). The evaluation of this process in such a huge frame faces some problems which need to be addressed. One of these difficulties is closely associated with the chronological attribution of a big part of the period's archaeological record due to scarce radiocarbon data.

Type 1	with rhomboid or rhombus-eye shape	
Type 2	with side appendages or cruciform	
Type 3	leaf-like	
Type 4	with peduncle but without flints	
Type 5	with a concave base	
Type 6	asymmetric	
Type 7	with peduncle and flints	

Figure 1: *Arrowhead types used for the study.*

The classification of the arrowheads in this period is based on the previous works performed around the typological formalization for the study area. They are mainly inspired

by morpho-descriptive typologies. Therefore, the classification contains a functional and morphological meaning. Arrowheads constitute a very representative tool group of the Late Neolithic and Chalcolithic. Their function is quite proved thanks to the studies in traceology, experimental archaeology and etnoarchaeology. Some well known examples are the spectacular findings of arrowheads still nailed into the victim bones, present in many burials from the 4th and 3rd millennium BC (i.e. San Juan ante Portam Latinam: Vegas 2007). We cannot forget the awesome finding of a full equipment Ötzi, the "Iceman", discovered in the Alps (Cave-Browne, 2016), and exceptionally conserved. Moreover, the existence of excavated sites (Ereta del Pedregal) in which the whole arrowhead operative chain process can be observed, has provided additional information (Juan-Cabanilles, 1994).

The arrowhead types present in the archaeological records have been classified in seven types following a morphological criterion, based on previous typologies for the study area (Juan-Cabanilles, 2008) (See Figure 1).

3 Bayesian classification process

Bayesian classification within the framework of archaelogical datation with lithic information will provide a probability distribution for the period to which an undated site belongs in which a given set of different types of arrowheads has been found. This probability distribution depends on the knowledge of the abundance of each type of arrowheads in each period, expressed via the posterior distribution for the probability associated with each type of arrowhead, and the posterior predictive distribution for the period of that particular updated site.

3.1 Dirichlet-multinomial inferential process

Let Y_{ij} be the random variable that describes the number of type j, $j = 1, \ldots, J$ arrowheads, of the total n_i collected in the sites belonging to period i, $i = 1, \ldots, I$. We define the random vector $Y_i = (Y_{i1}, Y_{i2}, \ldots, Y_{i,J-1})^{\mathsf{T}}$ and the probability vector $\boldsymbol{\theta}_i = (\theta_{i1}, \theta_{i2}, \ldots, \theta_{i,J-1})^{\mathsf{T}}$, where θ_{ij} is the probability that an arrowhead of period i is of type j. A probabilistic model for $Y_i \mid \boldsymbol{\theta}_i$ is the multinomial distribution, $\mathrm{Mn}(\boldsymbol{\theta}_i, n_i)$, with probability distribution

$$f(y_i \mid \boldsymbol{\theta}_i) = \frac{n_i!}{\left(\prod_{j=1}^{J-1} y_{ij}!\right) y_{iJ}!} \left(\prod_{j=1}^{J-1} \theta_{ij}^{y_{ij}}\right) \theta_{iJ}^{y_{iJ}}, \tag{1}$$

where y_i is an observation of Y_i, $y_{iJ} = n_i - \sum_{j=1}^{J-1} y_{ij}$ is the total number of arrowheads of type J in the sites of period i, and $\theta_{iJ} = 1 - \sum_{j=1}^{J-1} \theta_{ij}$ is the probability that an arrowhead of period i is of type J.

The combination of a multinomial sampling model with a conjugate Dirichlet prior distribution was proposed by Lindley (1964) and Good (1967) as the generalisation of the beta-binomial model. The Dirichlet distribution for $\boldsymbol{\theta}_i$ with parameters $\boldsymbol{\alpha}_i = (\alpha_{i1}, \ldots, \alpha_{iJ})^\top$, $\alpha_{ij} > 0, j = 1, \ldots, J$, $\text{Dir}(\boldsymbol{\alpha}_i)$, is a multivariate continuous distribution with joint density function

$$\pi(\boldsymbol{\theta}_i) = \frac{\Gamma(\alpha_{i+})}{\prod_{j=1}^{J} \Gamma(\alpha_{im})} \left(\prod_{j=1}^{J-1} \theta_{ij}^{\alpha_{ij}-1} \right) \theta_{iJ}^{\alpha_{iJ}-1}, \tag{2}$$

where $\Gamma(\cdot)$ represents the gamma function and $\alpha_{i+} = \sum_{j=1}^{J} \alpha_{ij}$.

We assume an inferential process for each $\boldsymbol{\theta}_i$, $i = 1, \ldots, I$ in the framework of the Dirichlet-multinomial process with a non-informative prior distribution for $\boldsymbol{\theta}_i$ that gives all the protagonism of the process to the data. There are many proposals for elicit the parameters $\boldsymbol{\alpha}_i$ in a non-informative way: Haldane's prior, Perks' prior or reference distance prior, hierarchical approach prior and Jeffreys' prior or common reference prior, and Bayes-Laplace prior. All them have good theoretical properties but they also have some small shortcomings. We choose the Perks' prior as a result of Alvares, Armero and Forte (2018). This prior was firstly proposed by Perks (1947), but recently it has been also obtained as the reference distance prior by Berger et al. (2015). This is a Dirichlet distribution with all parameters equal to $1/J$, where J is the number of arrow types. Figure 2 shows the density and other characteristics of a Perk's distribution with three categories.
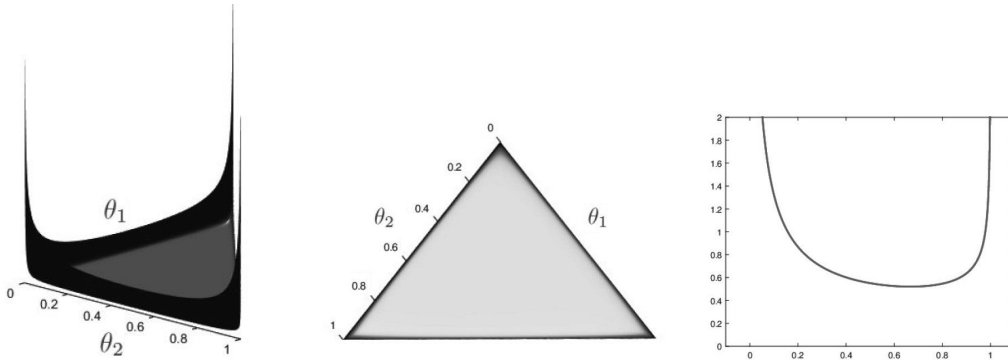

Figure 2: *Perks' distribution when the number of types of arrowheads is $J = 3$ (a), its projection onto the simplex triangle (b), and the marginal prior distribution for each individual component, a beta distribution with parameters $1/3$ and $2/3$, $Be(1/3, 2/3)$, which maintains high density values close to 0 and 1(c).*

The posterior distribution for $\boldsymbol{\theta}_i$ when data y_i are observed is also a Dirichlet distribution (Lindley, 1964; Good, 1967),

$$\pi(\boldsymbol{\theta}_i \mid y_i) = \text{Dir}(\alpha_{i1} = y_{i1} + (1/J), \ldots, \alpha_{iJ} = y_{iJ} + (1/J)). \tag{3}$$

This posterior distribution has an important and positive feature: never assigns absolute probabilities 1 or 0 to the presence of any type of headarrows. This fact avoids working with absolute values of the probabilities, 0 and 1, which would prevent future updates of their values generated by new data.

The marginal posterior distribution for each probability θ_{ij} is the beta distribution (Gelman *et al.*, 2014)

$$\pi(\theta_{ij} \mid y_i) = \text{Be}(\alpha_{ij}, \alpha_{i+} - \alpha_{ij}), \tag{4}$$

with posterior mean and variance α_{ij}/α_{i+} and $\alpha_{ij}(\alpha_{i+} - \alpha_{ij})/(\alpha_{i+}^2(\alpha_{i+} + 1))$, respectively.

3.2 Predictive process

After learning about the distribution of the proportion of arrowheads types in each site, we have to assign a probability distribution to the random variable that describes the period m^* to which a new undated site s^* belongs given that a total of n^* arrowheads $y^* = (y_1^*, \ldots, y_J^*)^{\mathsf{T}}$ have been observed in it. Following Bayes' theorem:

$$P(m^* = m_i \mid y^*, y) \propto P(Y^* = y^* \mid m^* = m_i, y) P(m^* = m_i \mid y), \ i = 1, \ldots, I, \tag{5}$$

where $y = (y_1, \ldots, y_I)^{\mathsf{T}}$ are the observed data in the previous estimation process and $Y^* = (Y_1^*, \ldots, Y_J^*)^{\mathsf{T}}$ is the random vector that describes the number of arrowheads of the different types that will be recorded in that new site. It is important to note that Y and Y^* in capital letters refer to the random vector that generate or will generate the data y and y^*, respectively, which we always represent by lower case letters. The asterisk is used to represent the subsequent random variables and observations of the prediction process.

The posterior predictive distribution in (5) is proportional to the product of two terms. The first one is:

$$P(Y^* = y^* \mid m^* = m_i, y) = \int P(Y^* = y^* \mid \boldsymbol{\theta}_i, m^* = m_i, y) \, \pi(\boldsymbol{\theta}_i \mid m^* = m_i, y) \, \mathrm{d}\boldsymbol{\theta}_i$$

$$= \int \frac{n^*!}{y_1^*! y_2^*! \cdots y_J^*!} \theta_{i1}^{y_1^*} \theta_{i2}^{y_2^*} \cdots \theta_{iJ}^{y_{J^*}} \frac{\Gamma(\alpha_{i+})}{\prod_{j=1}^J \Gamma(\alpha_{ij})} \theta_{i1}^{\alpha_{i1}-1} \theta_{i2}^{\alpha_{i2}-1} \cdots \theta_{iJ}^{\alpha_{iJ}-1} \mathrm{d}\boldsymbol{\theta}_i$$

$$= \frac{n^*!}{y_1^*! y_2^*! \cdots y_J^*!} \frac{\Gamma(\alpha_{i+})}{\prod_{j=1}^J \Gamma(\alpha_{ij})} \int \theta_{i1}^{\alpha_{i1}+y_1^*-1} \theta_{i2}^{\alpha_{i2}+y_2^*-1} \cdots \theta_{iJ}^{\alpha_{iJ}+y_{J^*}-1} \mathrm{d}\boldsymbol{\theta}_i$$

$$= \frac{n^*!}{y_1^*! y_2^*! \cdots y_{J^*}!} \frac{\Gamma(\alpha_{i+})}{\Gamma(\alpha_{i+}+n^*)} \prod_{j=1}^J \frac{\Gamma(\alpha_{ij}+y_j^*)}{\Gamma(\alpha_{ij})}.$$

The first probability in the integrand, $P(Y^* = y^* \mid \boldsymbol{\theta}_i, m^* = m_i, y)$, is associated with new experimental results in the presence of $\boldsymbol{\theta}_i$ and the data y from the estimation process

which are irrelevant due to the presence of $\boldsymbol{\theta}_i$. It is a multinomial probability computed from (1). The second term, $\pi(\boldsymbol{\theta}_i \mid m^* = m_i, y)$, is the Dirichlet posterior distribution for $\boldsymbol{\theta}_i$ given in (3).

The second element in the product in (5), $P(m^* = m_i \mid y)$, can be estimated as the proportion of sites in the sample for each of the periods under consideration (Barber, 2012).

4 East of the Iberian Peninsula sites during the 4th and 3rd millennium cal BC

We apply the classification procedure above to a set of undated sites in the East of the Iberian Peninsula during the 4th and 3rd millennium cal BC. Data for the inferential process of the study come from 31 archaeological sites radiocarbon dated with arrowheads, clear contexts and stratigraphy.

4.1 Inferential process

All 14C dated sites have been filtered using only those whose radiocarbon dates come from short-lived singular samples. The final levels used for the periodization are: Arenal de la Costa (Bernabeu, 1993), Barranc del Migdia (Soler Díaz et al., 2016), Beniteixir (Pascual Beneyto, 2010), Camí de Missena (Pascual Beneyto, Barberà and Ribera, 2005), Colata (Gómez Puche et al., 2004), Cova del Randero (Soler Díaz et al., 2016), Cova dels Diablets (Aguilella, Olaria Puyoles and Gusi Jener, 1999), Jovades (Bernabeu, 1993), La Vital (Pérez-Jordà et al., 2011), Niuet (Bernabeu, Pascual Benito, Orozco Köhler, Badal García, Fumanal García and García Puchol, 1994), and Quintaret (García Puchol et al., 2014). These sites are located in the eastern Mediterranean area. Figure 3
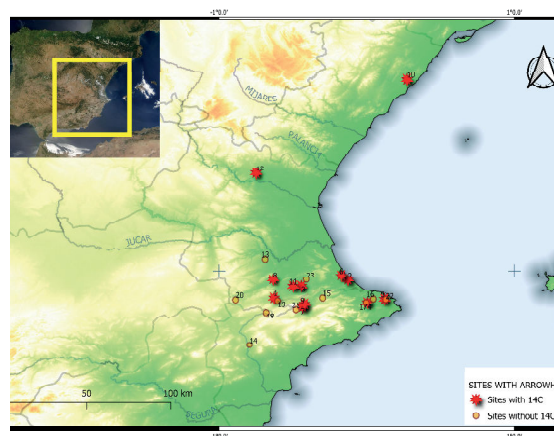

Figure 3: *Situation map of the sites with arrowheads present in the study area.*

shows a map with the dated sited as well as the sites without 14C datation whose chronological classification is the final object of this study.

Based on the chrono-stratigraphic and available expert information, we have proposed five intervals or chronological periods organization comprised between ca. 4600-3200 cal BC. Table 1 includes the period of each of the periods considered as well as the sites included in each of them.

Each site usually contains many different archaeological levels attached to different moments of occupation. In this specific case, archaeological contexts containing arrowheads have been dated through radiocarbon determinations. Some of these sites contain different dated levels in which arrowheads were present. Hence we have described them with the name of the site and a number to differentiate them. Based on the chrono-stratigraphic and available expert information, we have proposed five successive intervals or chronological periods comprised between ca. 4600-2150 cal BC. These periods have resulted from the application of Bayesian radiocarbon modeling methods to the archaeologic information available for each period.

Table 1: *Periods and sites extracted from clear archaeological contexts with radiocarbon determinations.*

Sites 14C dated	Period
Jovades 1, Jovades 2, and Niuet 1	1
Colata 1, Colata 2, Jovades 3, Jovades 4, Niuet 2, and Quintaret	2
Beniteixir, Diablets 1, Diablets 2, Diablets 3, Jovades 5, La Vital 1, La Vital 2, Migdia 1, Missena 1, Niuet 3, Niuet 4, Randero 1, and Randero 2	3
La Vital 3, Migdia 2, Missena 2, and Missena 3	4
Arenal Costa, La Vital 3, Missena 4, Missena 5, and Missena 6	5

Table 2: *Posterior Dirichlet distribution for the proportion of arrowheads from type 1 to type 7 in each of the periods considered.*

Period	Posterior distribution
1	Dir(15/7, 22/7, 8/7, 1/7, 1/7, 1/7, 1/7)
2	Dir(29/7, 36/7, 15/7, 8/7, 1/7, 1/7, 1/7)
3	Dir(43/7, 1/7, 43/7, 64/7, 29/7, 1/7, 71/7)
4	Dir(15/7, 1/7, 15/7, 8/7, 15/7, 1/7, 43/7)
5	Dir(1/7, 1/7, 1/7, 15/7, 1/7, 8/7, 36/7)

Table 2 includes the posterior distribution of the different types of arrowheads in each of the periods considered. In all of them the selected prior distribution is the Perk
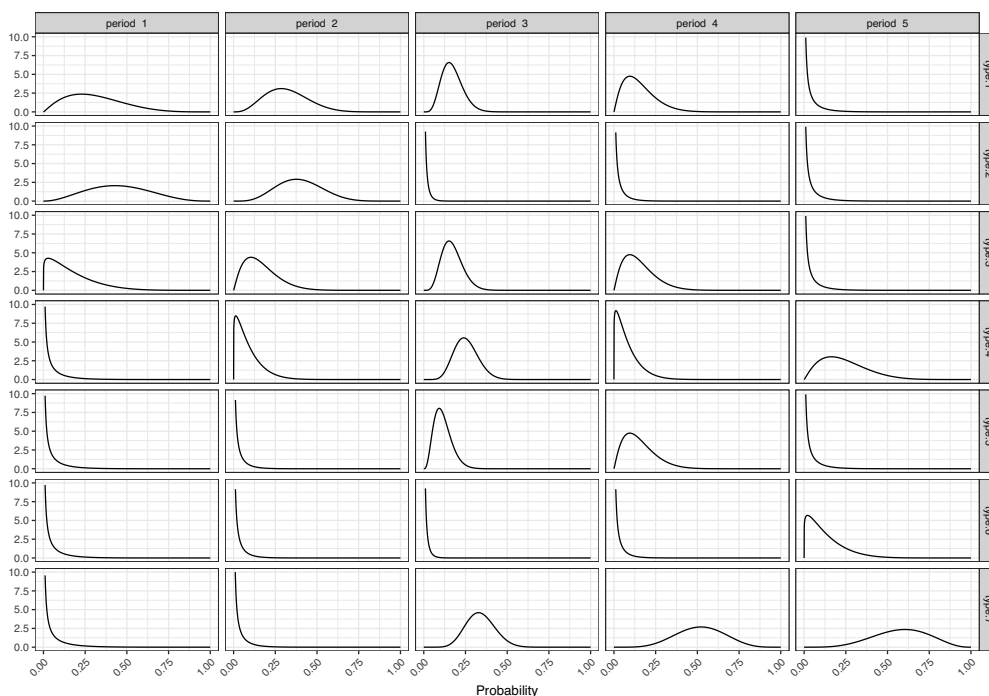
Figure 4: *Posterior marginal distribution for the probability associated with each type of arrowhead in each of the periods in the study.*

distribution Dir(1/7, 1/7, 1/7, 1/7, 1/7, 1/7, 1/7). Therefore, those parameters of the corresponding posterior distribution that continue to be worth 1/7 correspond to those types of arrows that have not been observed in the sample.

Table 3 shows the posterior mean for the probability associated with each type of arrowhead in each of the periods in the study. Figure 4 shows the posterior marginal distribution of the probability of the different types of arrowheads in each of the five chronological periods considered. Results in Table 3 and Figure 4 indicate that the distribution of the different types of arrowheads is very similar in Periods 1 and 2: Type 1 and 2 arrowheads are the most abundant and about the 75% and 70% of the total of arrowheads in both periods are type 1 or 2. Type 3 arrowheads have poor relevance in both Periods and types 4, 5, 6, and 7 are virtually nonexistent. In Period 3, we find practically no type 2 and 6 arrowheads. The remaining arrowheads in this period have a presence quite similar but type 4 and 7 have a slightly higher presence. Period 4 shows a large presence of type 7 arrows and, to a lesser extent, of type 1, 3 and 5 arrows (probabilities of about 0.15). Arrowheads of type 2 and 6 have no relevance. Approximately 57% and 24% of the arrows of Period 5 are of type 7 and 4, respectively. The remaining arrowhead types, except possibly those of type 6, are essentially irrelevant.

Table 3: *Posterior mean of the probability associated to each type of arrowhead in each of the periods of the study.*

Type	Period 1	Period 2	Period 3	Period 4	Period 5
1	0.3061	0.3187	0.1706	0.1531	0.0159
2	0.4490	0.3956	0.0040	0.0102	0.0159
3	0.1633	0.1648	0.1706	0.1531	0.0159
4	0.0204	0.0879	0.2540	0.0816	0.2380
5	0.0204	0.0110	0.1151	0.1531	0.0159
6	0.0204	0.0110	0.0040	0.0102	0.1270
7	0.0204	0.0110	0.2817	0.4387	0.5714

4.2 Predictive process

Undated sites between the 4th and 3rd millennium cal BC. used to explore the predictive approach include burial sites, villages, and caves: Barranc Cafer 2, Barranc Parra 3, Casa Colorà, Cova Ampla del Montgó, Cova Santa Vallada B, Cova de les Aranyes, Cova dels Anells, Cova del Negre, Cova del Petrolí, Cova Pardo, Cova Santa Vallada A, Ereta I, Ereta II, Ereta III, Ereta IV, Escurrupenia, Font de Mahiques, Garrofer 3, Garrofer K, Garrofer I-J, Rambla Castellarda, Sima de la Pedrera, Niuet s3, Torreta UE1, and Torreta UE2 (See Figure 3).

The posterior probability that a new site belongs to each of the periods considered was estimated as 0.15 for Periods 1, 4 and 5, 0.20 for Period 2, and 0.35 for Period 3.

Figure 5 presents the posterior predictive distribution of the period to which the above undated sites belong, whose only available information is based on the number and type of arrows found collected.

The results obtained show a high concordance with the expert information provided by archaeologists. Thus, for example, in those sites that present stratigraphic correlations (Ereta del Pedregal and La Torreta) the chronological evaluation obtained from the predictive approach is consistent with the chrono-statigraphical information. The case of Cova Santa de Vallada B is interesting, which from the archaeological information is situated in phase 3-4. However, based on Bayesian modeling, this indicates that it should be located in Period 3. This aspect is totally coherent not only because of the typology of the arrowheads themselves but also because of the presence of other diagnostic elements such as the presence of metal and the absence of bell-beaker ceramics. The result is totally consistent with the cases of Casa Colorà and Cova del Garrofer I-J, which both the previous experience and the Bayesian application place in Period 3. Finally, there are some cases in which the results qualify the chronological proposal established by expert knowledge, such as the case of Barranc de Parra 3, where previous knowledge places it in Period 2-3 but predictive analysis places it either in Period 1 or in Period 4. In this sense, we must bear in mind both that there may be a persistence of certain types

of arrowheads throughout the entire sequence analyzed, as is the case of the arrowheads of the peduncle, as well as the possible reuse of projectiles located in places of habitat as has been documented in the Clovis culture, North America. In this sense both the incorporation of other complementary diagnostic archaeological information (presence of metal and bell-shaped ceramics) may help to establish a more precise chronology.
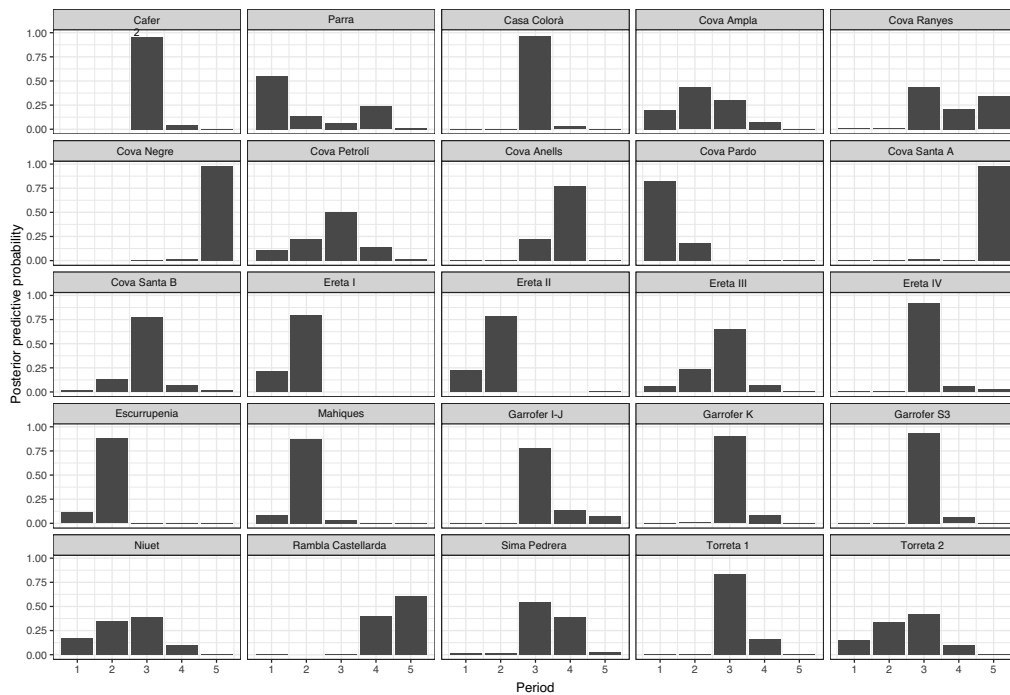

Figure 5: *Posterior predictive distribution associated with each chronological period for each non-dated site in the study.*

Conclusions

In short, results obtained present a good agreement with the expert information of the archaeologists, so it is a proposal that can be very useful in archaeological research. However, there is no doubt that both the application of stratigraphic contexts of higher resolution and the use of associated radiometric dates related to the most diagnostic archaeological items will allow to improve this approach.

Acknowledgements

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