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Bayesian Estimation Dating of Lithic Surface Collections

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Abstract Surface assemblages represent the most accessible, representative sample of the archaeological record for the study of human socio-ecological systems at regional scales. However, the difficulty in developing suitable chronological frameworks from surface assemblages has limited their use. Additionally, surface scatters are composed of artifacts that can accumulate across multiple occupational episodes. A challenge to chronology building in such surface contexts is the necessity to assess the probability of occupation during each time period. We describe a new method of dating surface lithic assemblages using empirical Bayesian methods, with an example from northeastern Spain. We use Bayesian methods to estimate the probability of occupation during 11 temporal periods (*ca.* 13,000–4,200 cal BP) for a sample of 25 lithic surface assemblages. A Bayesian approach allows us to combine prior knowledge, with different degrees of uncertainty, about the temporal sensitivity of projectile forms statistically derived from a regional calibration data set of 35 dated assemblages to estimate the age of each surface collections probabilistically. This approach provides new insight into the settlement history of the Maestrat in the first half of the Holocene, during the transition from foraging to food production, and offers a powerful tool to archaeologists for the dating of surface collections.

Keywords Lithic analysis · Surface archaeology · Chronology · Bayesian methods · Landscape archaeology · Spain

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Introduction

Relative Chronology Methods on Surface Lithic Assemblages

Assessing the age of ubiquitous surface lithic scatters is a key methodological and interpretive issue for landscape archaeology throughout the world. While excavated sites can provide detailed information about human use of resources and associated paleoenvironmental conditions, they represent a tiny fraction of socio-ecological systems in which human groups operate, whether hunter-gatherers or agriculturalists. Yet, systematic study of regional-scale socio-ecological systems faces important challenges. One of the most common is the difficulty in developing a sufficiently fine-resolution chronological framework for the archaeological record at these spatial scales. It is currently impractical to carry out test excavations to sample landscapes at hundreds or thousands of localities to collect regional data about human land use. Moreover, many residues of human activity are limited to surface scatters of durable lithics and sometimes ceramics, without stratigraphic context—and ceramics are only available for part of the Holocene record and in only some regions. Numerical chronological methods that can be applied directly to lithic materials include thermoluminescence (TL) and surface exposure cosmogenic radionuclide (CRN) dating. But TL can only be applied to buried lithics and available CRN methods are only suitable for dating lithic artifacts older than 100 ka (Akçar *et al.* 2008; Ivy-Ochs *et al.* 2001).

Relative chronology building, based on the seriation of artifact forms from stratigraphically reliable contexts, is a common approach for ceramics and also has been applied to lithic assemblages (O'Brien and Lyman 1999). However, seriation techniques assume that each assemblage was deposited during a single temporal period, and this assumption is often violated in surface assemblages that are cumulative palimpsests of multiple occupational episodes (Barton *et al.* 2004; Wandsnider 1992).

The importance of surface assemblages in the archaeological record and the need for high-resolution chronological frameworks for studying social change and the dynamic interactions of humans with their environments underscore the need for better methods estimating the ages of surface collections and unmixing the temporal palimpsests that characterize these assemblages. Rank-order probabilistic dating explicitly addresses this palimpsest issue, where multiple temporal periods may be represented at different probability thresholds in a given surface collection. In prior work in the Mediterranean region of Spain, Barton and colleagues (1999, 2002, 2004) developed a Temporal Index (TI) by assigning rank-order probability estimates, between zero and one, for different time intervals (Middle Paleolithic, Upper Paleolithic, Late Upper Paleolithic and Epipaleolithic, Early Neolithic, and Late Neolithic) using combinations of the presence or absence of artifact forms with different degrees of chronological sensitivity. TI was originally designed for chronological statistical "unmixing" of surface assemblages and identifying long-term changes in land-use patterns for randomly sampled survey units. However, the chronological resolution of the periods defined by TI was coarse because of limited archaeological evidence for relative chronology building and the use of simple statistical techniques.

Bayesian techniques build conceptually on rank-order probabilistic dating, with more sophisticated statistics that make better use of prior knowledge of regional archaeological sequences and artifact collections derived from stratigraphic contexts, to provide finer-scale chronologies and better measures of reliability in age estimates for surface artifact assemblages. We apply Bayesian inference to a series of surface assemblages from eastern Spain to develop a more robust method for estimating their ages on the basis of temporally sensitive artifact forms.

Bayesian Methods

Bayesian methods comprise a branch of statistics that uses probabilities as means of measuring the belief on a particular hypothesis being true. It emphasizes that the interpretation of data is conditional on the information available about a set of phenomena at a given time and, consequently, on an individual's understanding of it (Buck *et al.* 1996:1).

The core of the Bayesian inference connects *prior knowledge* about a given phenomenon (expressed as a prior probability) and a *conditional probability* (also referred as a likelihood function) derived from a probability model for new data observed. Both prior and conditional probabilities are used for calculating the resulting *posterior probability* values of different possible hypothesis given the observed evidence. Put in its simplest mathematical form, Bayesian inference can be expressed as

$$\mathrm{P(H|D)}\alpha\ \mathrm{P(H)} * \mathrm{P(D|H)} \tag{1}$$

where the posterior probability P(H|D) is proportional to the prior probability P(H) times the conditional probability P(D|H) (see Buck *et al.* 1996:20–21; Ortman *et al.* 2007:244–245).

The fundamental difference between the classical and Bayesian approaches to statistical inference lies in the use of prior information (Buck *et al.* 1996:17). For this reason, it has been suggested that Bayesian methods may be especially useful in archaeological contexts where the goal is to interpret new data on the basis of existing knowledge of the archaeological record (Cowgill 2002). Bayesian methods have been explored for a variety of archaeological applications, including radiocarbon dating (Culleton *et al.* 2012; Riede and Edinborough 2012), assessing the age of individuals at death from skeletal and dental morphology (Gowland and Chamberlain 2002; Heuzé and Braga 2008), spatial analysis (Robertson 1999), artifact and site locational predictive modeling (Finke *et al.* 2008; Ford *et al.* 2009), and geophysical survey (Buck *et al.* 1996).

Recently, Bayesian methods have been extended to a limited extent to seriation-like age estimates from archaeological materials. These applications can be divided into model-based and empirical-based Bayesian approaches.

Model-based Bayesian approaches have been applied primarily on small samples of published archaeological data, including geometric microliths and grave goods (Buck and Sahu 2000; Halekoh and Bach 2004). This work has focused on the use of stochastic models such as Markov Chain and Monte Carlo methods to explore the temporal variability of the estimated posterior distribution values. *Empirical-based Bayesian approaches* (EBB), on the other hand, compute a prior probability density function from dated assemblages and then use it to estimate the posterior probability of the age of an undated sample (Ortman *et al.* 2007). EBB has been shown useful with large data sets composed of with variably sized artifact samples, including administrative site inventories (e.g., state Historic Preservation inventories) from survey and excavation, to estimate the age of surface collections. Especially when based on artifact collections recovered from different projects that may have employed different recovery methods, it is important to develop calibration data sets that can deal with potential inter-observer variability and biases as part of the workflow converting prior knowledge to prior probability.

Here, we apply an EBB approach to temporally sensitive lithic forms to estimate the probability of occupation at 25 Late Pleistocene to mid-Holocene surface localities in eastern Spain. As discussed below, we focus on lithics here because of their ubiquity in surface collections through the mid-Holocene. For much of the Neolithic, ceramics are poorly preserved and rare in surface collections, and other materials are found at even much lower frequencies than ceramics. It is important to note that an EBB approach allows us to evaluate the temporal sensitivity of different lithic forms empirically on the basis of their appearance in assemblages dated by other means (e.g., radiocarbon).

Study Area and Archaeological Settings (13,000–4,200 cal BP)

The surface lithic collections analyzed in this paper come from the Upper Maestrat region of eastern Spain, and form one component of a broader research project on interrelationships between settlement dynamics, land use changes, and rock art at regional and local analytical scales, between the end of the Epipaleolithic and the Bell Beaker periods (*ca*. 13,000–4,000 cal BP) (Fernández-López de Pablo 2005).

The study area is defined by the watershed of the upper Coves River. The Coves River valley is filled by Quaternary detritic and colluvial materials. It lies at an average elevation of 500 m amsl and is bordered by calcareous mountain ranges that rise to between 700 and 1,100 m amsl. Recurrent archaeological research in this area (Durán and Pallarés 1915–1920; de Val 1977; Fernández-López de Pablo 2005; Román 2011) have documented more than 20 lithic scatters, most on terraced fields, grouped spatially into two clusters located about 5 km from each other (Fig. 1). The first cluster, in the northern foothills of the Serra d'en Galcerán, is composed of eight lithic scatters unevenly distributed within a radius of 2 km. The second cluster, located on limestone plateaus on both sides of the Valltorta Canyon, include 11 lithic scatters distributed within a radius of 3 km. Minor concentrations of surface lithics are found in secondary order drainages of the Sant Miquel and Hondo valleys, and two lithic scatters are located at higher altitude in mountain ranges peripherical to the main two clusters. Previous analyses have suggested, on the bases of individual temporally diagnostic artifact forms, that occupations that produced these surface lithic assemblages date to some between the Epipaleolithic and the Bell Beaker periods (Fernández-López de Pablo *et al*. 2002; Fernández-López de Pablo 2005).

The regional archaeological chronology has been defined on the basis of comparative stratigraphy, morphological changes in ceramic and lithic assemblages, and radiocarbon dating (Table 1). It is divided into 11 chronological periods: the Epipaleolithic or Epimagdalenian (*ca*. 13,000–11,400 cal BP), Sauveterrian (*ca*. 11,400–10,400 cal BP), Notch and Denticulate Mesolithic (*ca*. 10,400–8,600 cal BP), Late Mesolithic Phase A (*ca*. 8,600–8,000 cal BP), Late Mesolithic Phase B (*ca*. 8,000–7,600 cal BP), Early Cardial Neolithic (ca. 7,600–7,200 cal BP), Epicardial Neolithic (ca. 7,200–6,800 cal BP), Postcardial Neolithic (*ca*. 6,800–6,200 cal BP), Middle

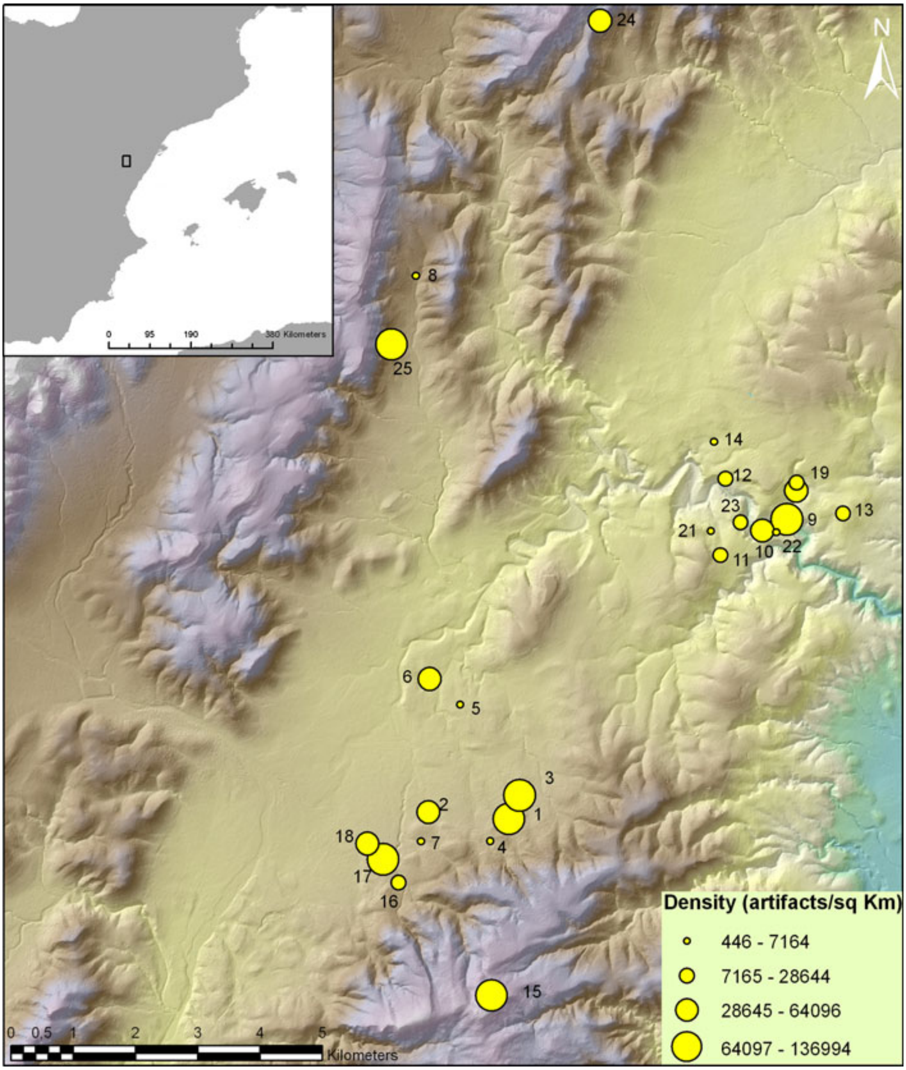

Fig. 1 Study area. Spatial distribution of the surface lithic scatters with projectile points. *1* Rueda, *2* Mas del Gat, *3* Canals, *4* Antona, *5* Clos, *6* Mitreres, *7* Mas del Viudo, *8* Mas del Riu, *9* Puntal, *10* Rompuda, *11* Peraire, *12* Bastida, *13* Matà, *14* Cavalls, *15* Sant Joan, *16* Sanç D, *17* Sanç C, *18* Sanç B, *19* Josep, *20* Llidoner, *21* Mallaeta, *22* Estaró, *23* Serretó, *24* Mas Blanc, *25* Mas de Martí. *Proportional symbols* represent artifact densities classified in quantiles

Neolithic (*ca*. 6,200–5,600 cal BP), Late Neolithic and Chalcolithic (*ca*. 5,600–4,500 cal BP), and Bell Beaker early Bronze Age (*ca*. 4,500–4,200 cal BP). Below, we briefly review the most salient aspects of the lithic assemblages of each of these periods for chronology building.

The Epipaleolithic displays a clear continuity with previous Magdalenian lithic traditions, dominated by backed bladelets for use as the tips of composite projectile weapons (Aura *et al.* 2011; Villaverde *et al.* 2012). The Sauveterrian uses geometric microliths, characterized by scalene triangles and pygmy crescents, and backed bladelets for projectile weapons. This lithic complex is poorly represented in the

Table 1 Proxy data for the regional archaeological sequence (*ca.* 13,000–4,000 cal BP) in eastern of Spain

Chronological periods	**EPI**	**SAU**	**NDM**	**LMA**	**LMB**	**ECN**	**EEN**	**PN**	**MN**	**LN&CH**	**BB**
cal BP	13000-11600	11600-11000	11000-8600	8600-7900	7900-7600	7600-7200	7200-6800	6800-6200	6200-5600	5600-4500	4500-4200
Economic features											
Pottery											
Domestic cattle											
Domestic ovis/capra											
Cereal crops											
Villages											
Copper metallurgy											
Projectile classes											
Backed bladelets			No data								
Triangles											
Crescents											
Trapezes											

Upper Maestrat region, with Abric de Filador serving as the reference site (García-Argüelles *et al.* 2005). Further away, Sauveterrian assemblages have been also identified at Parco and Santa Maira caves (Aura *et al.* 2006; García-Argüelles *et al.* 2009). Sauveterrian assemblages are more common in other southern European regions such as southern France or northern Italy, and there is some debate over whether the Sauveterrian even exists as a discrete lithic industry in the East of Spain or is better considered a variant of the preceding Microblade Epipaleolithic (Aura *et al.* 2011).

The Notch and Denticulate Mesolithic is characterized by flake debitage and notched and denticulated tools, and is best represented at sites in Catalonia and the Ebro valley (Aura *et al.* 2011; Vaquero 2004). The Late Mesolithic includes bladelet debitage, use of the micro-burin technique of bladelet reduction, and geometric microliths of Tardenoisian tradition elsewhere in Europe for projectile weapons. The Late Mesolithic is subdivided into two phases: in the earlier phase (A), geometrics are dominated by trapeze forms, while they are dominated by triangles in the later phase (B) (Martí *et al.* 2009).

The Neolithic is divided into temporal phases on the basis of changes in ceramic decoration. However, there are also differences in the form of lithics used for projectile tips during the Neolithic (Fig. 2).

The Early Cardial Neolithic represents the first introduction of ceramic and domesticates in the Mediterranean region of Spain, with classic Cardial ware ceramics. Recent work also has distinguished a "pre-cardial subphase" (7,600–7,450 cal BP) with impressed decoration of Ligurian style (Bernabeu *et al.* 2010).

Early Cardial Neolithic microliths display technological and morphological differences from previous Final Mesolithic industries. First, blade debitage is produced using a different core morphology that results in different blade width metric values (García-Puchol 2005). Second, the micro-burin technique is not used for blade/bladelet reduction in microliths production. Third, microlith morphology is different, with trapeze forms with both abrupt and bifacial retouch dominating lithic assemblages (Cava 2000; Juan-Cabanilles 2008). Crescents with abrupt retouch have also been reported in some Cardial sites such as Cova de l'Or (Juan-Cabanilles 2008). In contrast with the Late Mesolithic B, triangles with abrupt retouch are extremely rare or completely absent in Early Cardial Neolithic assemblages.

The Epicardial Neolithic is characterized by ceramics with incised and plastic decorations, and is best known from Cova Fosca (Olària and Gusi 2008) and the open-air site of Costamar (Flors 2009). However, Epicardial sites are widely distributed

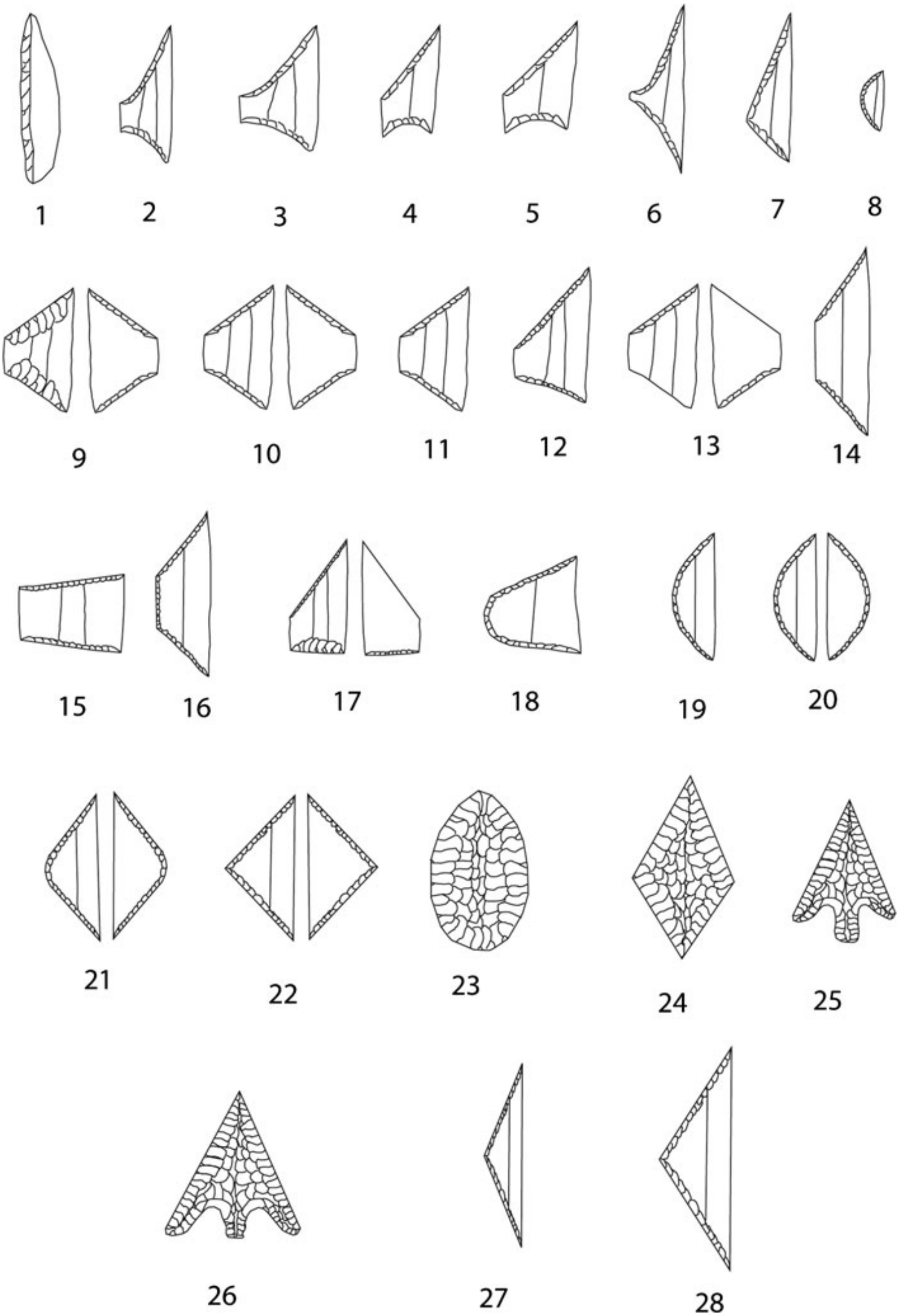

Fig. 2 Projectile point classes used in reference set for relative chronology building (see Table 2)

throughout the larger region (Juan-Cabanilles and Martí 2002). In the study area, as well as in the Ebro Valley and Cataluña regions, crescents with bifacial retouch dominate the geometric microliths in Epicardial Neolithic lithic assemblages.

The Postcardial Neolithic marks the appearance of regionally distinct ceramic styles. In the Valencian region, this phase is divided into two successive ceramic horizons characterized by combed and engraved decorative techniques (Bernabeu and Molina 2009). In Cataluña, three different ceramic styles have been recognized between the end of the Epicardial Neolithic and the onset of the Middle Neolithic (Molist *et al.* 1996). Among Postcardial lithic assemblages, microliths include different kinds of trapezes although the most diagnostic microlith form of this phase is the so-called rectangle (Juan-Cabanilles 2008) which is a particular kind of a short trapeze shape with parallel truncations.

The Middle Neolithic is mainly known from the funerary archaeological record. In central Cataluña, the so-called Sepulcros de Fosa is contemporaneous with the megaliths of the central Iberian Meseta and the Ebro valley (Gibaja 2003; Rojo *et al.* 2005). Microliths found at Megalith tombs in the Ebro Valley are dominated by elongated symmetric and asymmetric trapezes with abrupt retouch (Alegre 2005). A significant proportion of microliths display trihedral points on the apical parts of truncations, indicating the use of the micro-burin technique. In contrast, in the Middle Neolithic Sepulcros de Fosa archaeological entity, symmetric and asymmetric trapeze forms with combined inverse semi-abrupt and direct, flat retouch are the most common microlith classes.

Late Neolithic and Chalcolithic sites are widely distributed across the study area, including sites with numerous storage pits, houses, collective burials in caves, and lithic scatters. Because there are no recognized differences in temporally diagnostic lithic form, we group these periods together for the current analysis. Diagnostic projectile forms are mainly foliate and rhomboid shape bifacial projectile points (Juan-Cabanilles 2008). The morphological variation within and between these two major classes is not chronologically sensitive for differentiating subphases. Geometric microliths are much less frequent during this period than in prior Neolithic phases (Fernández-López de Pablo *et al.* 2008). Among those that are found, the microlith form of rectangular trapezoidal shape with inverse semi-abrupt retouch in the lower truncature is diagnostic for this period (Fernández-López de Pablo 2006).

Finally, the Bell Beaker displays considerable continuity with the Late Neolithic/ Chalcolithic periods in terms of settlement patterns and material culture. But distinctive forms of projectile points and lithic manufacture have been recognized in several studies (Juan-Cabanilles *et al.* 2006; Fernández-López de Pablo 2004; Gibaja *et al.* 2010). These mainly include tanged points with normal and elongated bilateral tangs.

Materials and Methods

In this study, we use the morphological and technological attributes of the stone components of projectile weapons—including backed bladelets, microliths, and bifacial points—as the basis for Bayesian age estimates of surface assemblages. We focused on lithic artifacts because the clearest assessment of this method would be with a single material class and technology that spans the entire chronological range of the sites in the study area (i.e., late Pleistocene through mid-Holocene) and is commonly preserved in surface assemblages. Chipped stone is the only artifact class that meets this criterion. Of chipped stone artifacts, changing form of projectile elements have consistently had the most consistent temporal signal, in a large part because they are components of relatively complex weapons systems. We recognize, however, that even with the durability of chipped stone, projectile elements often are rare in lithic assemblages and are not infrequently lacking in surface collections. However, the two prior applications of Bayesian methods to estimating the age of artifact assemblages that we are aware of only apply it to ceramics (Ortman *et al*. 2007; Roberts *et al*. 2012). Ceramics are only present in some Holocene contexts (i.e., Neolithic and later) and are also rare or absent in many surface collections of the study region. Thus, while lithic projectile tips are well suited to testing the method of Bayesian dating described here, it will be useful to expand these methods to a wider range of artifact forms that can carry chronological signals.

Stone projectile elements are closely linked to prehistoric weapons systems and, in turn, to hunting behaviors (Shott 1996, 1997). From the Late Pleistocene through mid-Holocene, hunting behaviors and associated weapons systems underwent vectored change as prey shifted across the Pleistocene/Holocene boundary, as human demography and settlement changed, and as hunting and gathering economies were replaced by food production (Villaverde *et al*. 1998; Barton *et al*. 2004; Fernández-López de Pablo *et al*. 2009). This kind of vectored change, along with the consistent representation of projectile elements in lithic assemblages, makes them a good artifact category for relative chronology building. Changes in the frequency of backed bladelets and geometric microliths have been commonly used in prior work for seriation of Epipaleolithic and Mesolithic industries (Fortea 1973; Utrilla *et al*. 2009), and recent studies have focused on diachronic variability in Neolithic microliths and bifacial points (Juan-Cabanilles 2008; Niekus 2009; Fernández-López de Pablo *et al*. 2008). We recognize that some of the widely recognized projectile classes may in fact be different stages in the life history (manufacture, use, and discard) of a single weapons armature form (Neeley and Barton 1994; Barton and Neeley 1996).

In order to generate probability values for the age of occupation represented by surface collections considered in this study, we followed four steps: (1) define a reference set of projectile element classes that can be used with our sample of 25 surface lithic assemblages, (2) create a regional calibration data set for the reference classes from assemblages in stratigraphically secure contexts for estimating the occurrence of each artifact class within the chronological periods considered, (3) convert this prior knowledge into probabilities, and (4) calculate posterior probabilities for estimating the age of the surface collections.

Defining of a Reference Data Set

The reference set of projectile element forms defined spans the range lithic of morphological and technological variability found within the requisite time frame for this region. This reference set, described in Table 2 and Fig. 2, represents 28 potentially chronologically sensitive classes within three broad technological groups: backed bladelets (class 1), geometric microliths (classes 2–24), and bifacial projectile points (classes 25–28). This list is partially based on long-use typological systematics for the periods analyzed in this work (e.g., Fortea 1973; Juan-Cabanilles 2008), as well as more recent metric, technological studies (García-Puchol 2005; Fernández-López de Pablo *et al*. 2008).

Table 2 Description of projectile classes used in reference set for relative chronology building (see Fig. 2)

1: Backed bladelet (generic)
2: Trapeze of two concave sides and width higher than 10 mm
3: Trapeze of two concave sides and width higher than 10 mm
4: Trapeze of one concave side and width lower than 10 mm
5: Trapeze of one concave side and width lower than 10 mm
6: Triangle "Cocina" type
7: Scalene triangle
8: Hyperpygmee crescent (lower than 10 mm length)
9: Trapeze of combined inverse semi-abrupt and plate direct retouch
10: Trapeze of simple bifacial retouch
11: Symmetric trapeze of steep retouch
12: Asymmetrical trapeze of steep retouch
13: Symmetric or asymmetrical trapeze of alternate retouch
14: Elongated symmetric or asymmetrical trapeze of alternate retouch (length is higher than width twice)
15: Rectangle
16: Symmetric or asymmetrical trapeze with retouch in the minor edge
17: Rectangular trapeze of bifacial retouch in the lower truncation
18: Short trapeze with the rounded and retouched minor edge
19: Crescent of steep retouch
20: Crescent of bifacial retouch
21: Triangle of bifacial retouch and round central vertex
22: Triangle of bifacial retouch
23: Foliate (generic) bifacial projectile point
24: Rhomboid (generic) bifacial projectile point
25: Tanged point
26: Developed tanged point
27: Elongated isosceles triangle of width lower than10 mm
28: Elongated isosceles triangle of width higher than10 mm

Converting Prior Knowledge to Prior Probabilities

A regional calibration data set of projectile elements from lithic assemblages in stratigraphically reliable contexts of our study area is needed to estimate the prior probability of temporal occurrence of projectile classes (Fig. 3, Table 3, and supplementary materials Tables SM1 and SM2). The calibration data set was selected from 35 assemblages that span the 11 chronological periods, and totals 1,492 projectile elements. To ensure accurate temporal associations in this data set, to the extent possible, we limit it to sites with the most reliable chronologies and stratigraphic integrity, eliminating sites without radiometric dates and those with a high probability of stratigraphic mixing (e.g., old excavations without stratigraphic controls or disturbed contexts in stratified sites). We also focus on assemblages with well-published lithic assemblages or collections analyzed by us.

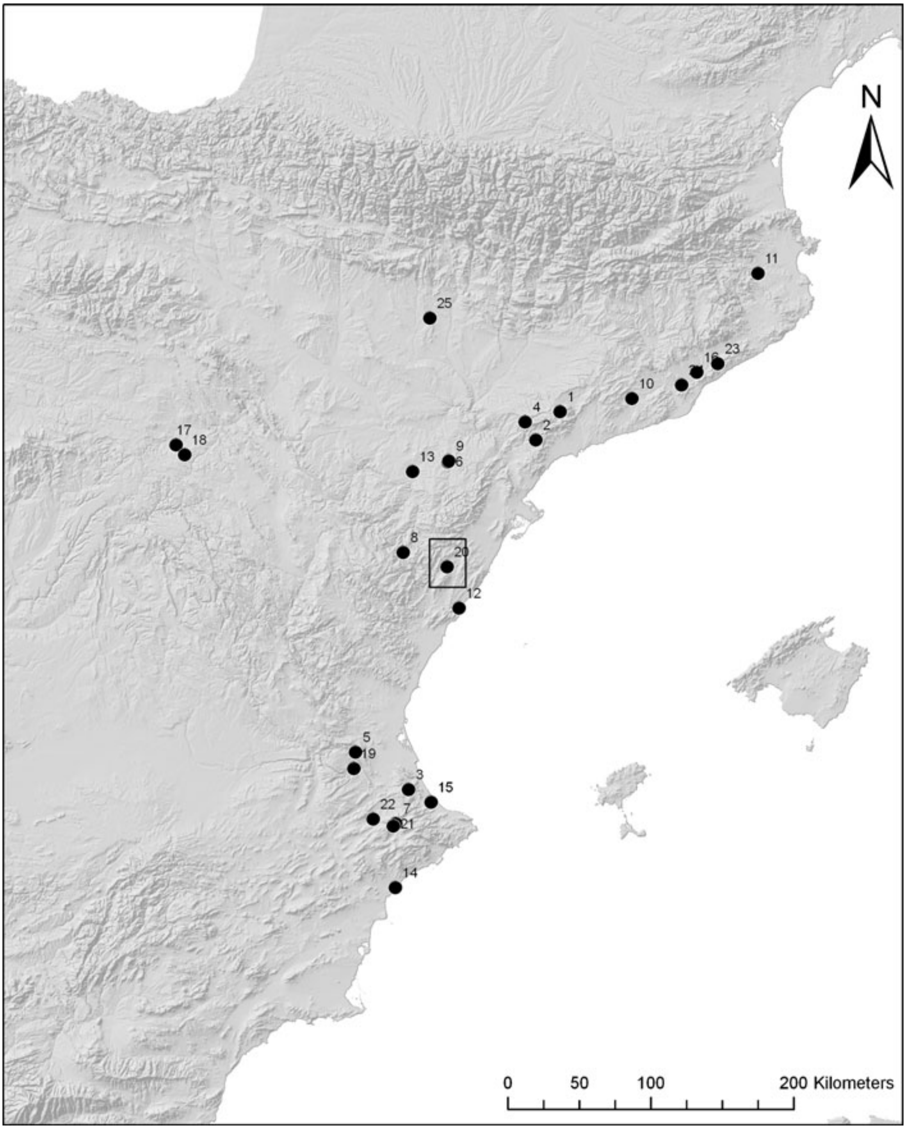

Fig. 3 Regional calibration data set. *1* Molí del Salt, *2* Sant Gregori, *3* Malladetes, *4* Filador, *5* Cocina, *6* Botiquería, *7* Benàmer, *8* Mas Cremat, *9* Secans, *10* Guixeres, *11* La Draga, *12* Costamar, *13* Alonso Norte, *14* Cerro de las Balsas, *15* Barranquet, *16* Can Grau, *17* Tarayuela, *18* Sima, *19* Ereta, *20* Tàbegues, *21* Niuet, *22* Arenal, *23* Can Martorell, *24* Carrer Paris, *25* Chaves. Study area outlined by *black rectangle*

For each assemblage, we calculated the frequency of each projectile element class relative to the total of all projectile elements. Then, we calculated the mean of the relative frequency for each projectile class for each of the temporal periods where that class was present. It is important to note that while we can estimate the probability that a projectile element is associated with a chronological period, numerical (i.e., calendrical) ages for each period have been estimated by radiometric dating of stratified deposits.

Table 3 Calibration data set assemblages organized by chronological periods

Chronological period	Cal BP	Duration	Calibration sites	*n*	Reference
Epipaleolithic (EPI)	13,000–11,600	1,400	Mallaetes VI	30	Casabó 2005
			Sant Gregori 1	25	Fortea 1973
			Sant Gregori 2	17	Fortea 1973
			Molí del Salt Asup	6	Vaquero 2004
Sauveterrian (SAU)	11,600–11,000	600	Filador 7	308	Garcia-Argüelles *et al.* 2005
			Filador 5–6	165	Garcia-Argüelles *et al.* 2005
Notches and Denticulates Mesolithic (NDM)	11,000–8,600	2,400	No projectile points		
Late Mesolithic Phase A (LMA)	8,600–7,900	700	Cocina I	41	Fortea 1973
			Botiqueria 2	71	Barandiarán 1978
			Benamer I	47	Jover 2011
Late Mesolithic Phase B (LMB)	7,900–7,600	300	Cocina II	56	Fortea 1973
			Botiqueria 4	26	Barandiarán 1978
			Mas Cremat VI–V	16	Gabarda 2010
			Secans IIb	33	Rodanés *et al.* 1995
Early Neolithic Cardial (ECN)	7,600–7,200	400	Chaves Ib	38	Cava 2000
			Guixeres	16	Mestres 1987
			Benamer II	4	Jover 2011
			La Draga	12	Palomo 2000
Early Neolithic Epicardial (EEN)	7,200–6,800	400	Costamar NII	4	García-Puchol 2009
			Chaves Ia2	6	Cava 2000
			Alonso Norte	37	Benavente & Andrés 1989
Postcardial Phase (PN)	6,800–6,200	600	Cerro de las Balsas	5	Fernández-López de Pablo 2013
			Guixeres Postcardial	7	Mestres 1988
			Barranquet Postcardial	21	Esquembre *et al.* 2008
Middle Neolithic (MN)	6,200–5,600	600	Can Grau	14	Marti *et al.* 1997
			Tarayuela	57	Alegre 2005
			Sima 1	13	Alegre 2005
			Sima 2	22	Alegre 2005
Late Neolithic and Chalcolithic (LN&CH)	5,600–4,500	1,100	Ereta I	68	Juan-Cabanilles 2008
			Tàbegues IIb	1	Fernandez-López de Pablo 2006
			Ereta II	66	Juan-Cabanilles 2007
			Niuet	17	Garcia 2005
Bell Baker (BB)	4,500–4,200	300	Ereta III/IV	160	Juan-Cabanilles 2007
			Arenal AII	11	Garcia 2005
			Can Martorell n inf	64	Palomo and Gibaja 2002
			Carrer Paris UE12	8	Gibaja *et al.* 2006

Calculating Posterior Probabilities

Posterior probabilities of occupation for each of the time periods were computed for the Upper Maestrat surface collections on the basis of projectile element counts for each surface assemblage (Table 2, supplementary materials). We use the Bayes' Theorem Equation employed by Ortman *et al.* (2007: Eq. 4) to estimate the probability $P(m_i \mid type_j)$ that a particular projectile class $type_j$ dates to chronological period m_i as follows:

$$P\left(m_i \middle| type_j\right) = \frac{P(m_i) * \sum_{j=1}^{n} P\left(type_j \middle| m_i\right)}{\sum_{l=1}^{k} P(m_l) * \sum_{j=1}^{n} P\left(type_j \middle| m_l\right)} \tag{2}$$

where $i=1$ to k are the 11 chronological periods, $j=1$ to n are the chronologically sensitive reference classes, $P(type_j \mid m_i)$ is conditional probability for class $type_j$ and chronological period m_i, and $P(m_i)$ is the prior probability of projectile class $type_j$ being represented in a chronological period m_i.

The posterior probability $P(m_i|d)$ of a given surface data set (d) dates to each chronological period according to its population of projectile points is expressed as follows:

$$P(m_i|d) = \frac{P(m_i)}{\sum_{l=1}^{k} P(m_l)} \tag{3}$$

where

$$P(m_i) = \left\langle n_j * P\left(m_l \middle| type_j\right) \right\rangle_j \tag{4}$$

and $P(m_i)$ indicates the probability of documenting a chronological period m_i according to the average of the number of artifacts n_j times the probability of period m_l be represented according to the presence of artifacts $type_j$.

Results

Prior Probability of Types Occurrence for Each Time Period

The prior probabilities that each of the projectile points is represented in each of the chronological periods are shown in Table 4 and expressed graphically as probability density distributions in Fig. 4. Almost half of the classes (46.4 %) are unimodal (2, 6, 8, 15, 17, 18, 20, 21, 23, 24, 25, 26, and 27), making them especially sensitive chronological markers. The remaining classes are bimodal (1, 4, 5, 7, 9, 10, 14, 16, 22, and 28) and multimodal (11, 12, 13, and 19) in temporal distribution. Of the non-unimodal classes, eight (28.6 %) are much more strongly associated with one period than others (1, 4, 7, 10, 13, 14, 19, and 22). This may indicate unrecognized misdating or stratigraphic mixing for a few cases in the reference data set. We do not need to ignore this information, however. The Bayesian approach incorporates this kind of chronological uncertainty about these and remaining six classes (21.4 % that are multimodal or which are not more strongly associated with one period) in a

Table 4 Calibration data set—prior probability of occurrence of each projectile type during the different chronological periods

	EPI	SAU	LMA	LMB	ECN	EEN	PN	MN	LN&CH	BB
1	0.2000	0.1100	0.0266	0.0594	0.0000	0.0072	0.0000	0.0000	0.0000	0.0000
2	0.0000	0.0000	0.0703	0.0214	0.0052	0.0000	0.0000	0.0000	0.0000	0.0000
3	0.0000	0.0000	0.0169	0.0042	0.0000	0.0000	0.0127	0.0135	0.0000	0.0000
4	0.0000	0.0000	0.0484	0.0075	0.0016	0.0000	0.0119	0.0000	0.0000	0.0000
5	0.0000	0.0000	0.0180	0.0000	0.0000	0.0000	0.0053	0.0265	0.0000	0.0000
6	0.0000	0.0000	0.0035	0.1330	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7	0.0000	0.0367	0.0054	0.0088	0.0011	0.0000	0.0026	0.0032	0.0000	0.0000
8	0.0000	0.2300	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
9	0.0000	0.0000	0.0000	0.0000	0.0230	0.0000	0.0275	0.0238	0.0000	0.0000
10	0.0000	0.0000	0.0000	0.0000	0.0841	0.0000	0.0000	0.0179	0.0000	0.0000
11	0.0000	0.0000	0.0132	0.0110	0.0266	0.0041	0.0136	0.0076	0.0000	0.0002
12	0.0000	0.0000	0.0184	0.0019	0.0073	0.0000	0.0231	0.0127	0.0005	0.0002
13	0.0000	0.0000	0.0037	0.0000	0.0397	0.0184	0.0246	0.0000	0.0000	0.0000
12	0.0000	0.0000	0.0092	0.0063	0.0013	0.0000	0.0000	0.0292	0.0022	0.0000
15	0.0000	0.0000	0.0000	0.0000	0.0044	0.0000	0.0920	0.0000	0.0049	0.0000
16	0.0000	0.0000	0.0000	0.0031	0.0063	0.0000	0.0063	0.0453	0.0052	0.0000
17	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2536	0.0000
18	0.0000	0.0000	0.0000	0.0000	0.0208	0.0000	0.0000	0.0000	0.0000	0.0000
19	0.0000	0.0000	0.0000	0.0061	0.0039	0.0552	0.0000	0.0229	0.0000	0.0000
20	0.0000	0.0000	0.0000	0.0000	0.0236	0.0951	0.0159	0.0005	0.0025	0.0091
21	0.0000	0.0000	0.0000	0.0000	0.0132	0.0000	0.0000	0.0000	0.0000	0.0000
22	0.0000	0.0000	0.0000	0.0000	0.0444	0.0000	0.0079	0.0000	0.0000	0.0000
23	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0988	0.0660
24	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2060	0.1193
25	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0273	0.2327
26	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0074	0.0530
27	0.0000	0.0000	0.0000	0.0134	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
28	0.0000	0.0000	0.0000	0.0000	0.0033	0.0000	0.0000	0.0579	0.0000	0.0000

probabilistic framework for assessing the reliability of age estimates on the basis of lithic artifacts.

It is important to reiterate that the goal is not to identify an artifact form that best signals a particular period or to identify the period that most closely associated with an artifact form. Rather, the goal is to quantitatively assess our level of confidence in the association of each projectile tip form with each of the chronological periods identified from stratified, radiometrically dated deposits. We may have no confidence that a projectile form is associated with a period (prior probability$\simeq$0). We can also have some confidence that a form is equally associated with two periods (prior probability=0.5 for each) or only with one period (prior probability$\simeq$1.0 for that period).

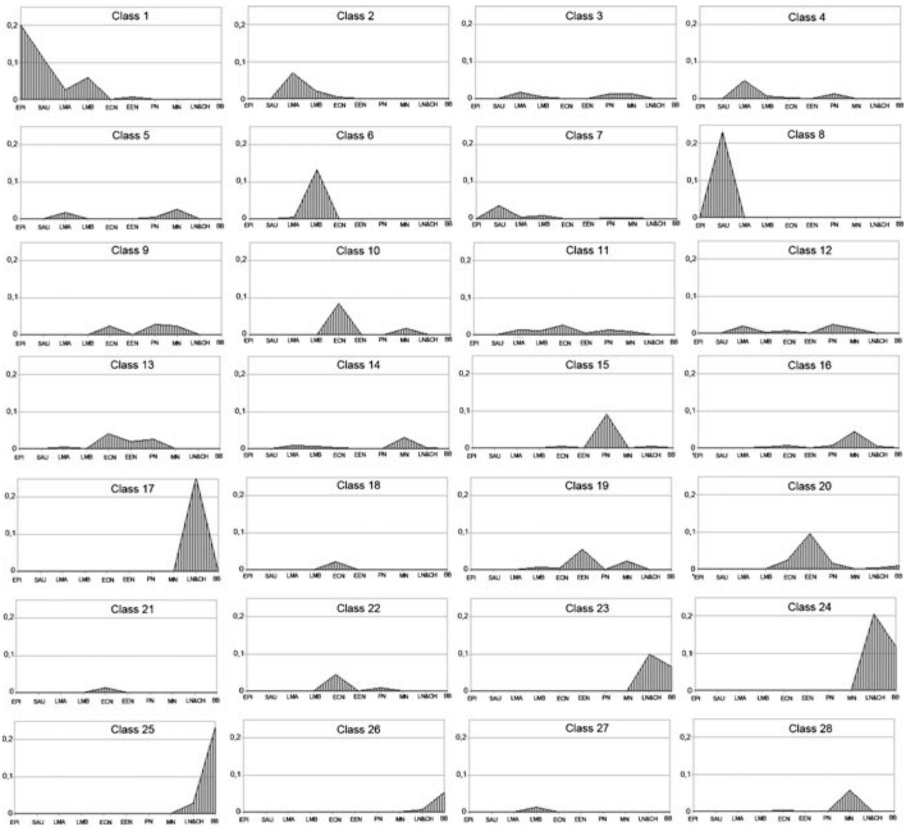

Fig. 4 Calibration data set. Prior probability density distributions for each of the 28 projectile classes used in the analysis. Chronological periods shown on the *x*-axis; probability of occurrence in each period shown on the *y*-axis. All graphs are to the same scale

Posterior Probability and Estimating the Age of Surface Collections

The posterior probabilities shown in Table 5 and Fig. 5 estimate the likelihood for each assemblage that it represents material from each of the different temporal periods. This explicitly and quantitatively expresses the palimpsest nature of surface collections, expressing both our prior knowledge and our uncertainty about the archaeological record. It also provides a powerful new method to unmix the chronological signals from such palimpsest collections by providing an assessment of the probability that an assemblage derives from each of the chronological periods. An assemblage that contains a mixture of artifacts from different periods of occupation will have non-zero posterior probabilities—or even a multi-modal probability distribution—for those periods. When interpreting the posterior probabilities, it is also important to remember that they must all sum to 1.0. So it is the relative strength of the posterior probabilities that must be assessed, not their absolute value. For example, an assemblage that is only associated with one period would display a value of 1.0 for that period and 0 for all other periods. But an assemblage for which half of the artifacts derive from one period and half from another would display values of 0.5

Table 5 Surface collections data set—calculated posterior probabilities of occupation during each chronological periods for each surface collection, based on frequencies of projectile classes

Site	EPI	SAU	LMA	LMB	ECN	EEN	PN	MN	LN and CH	BB
Rueda	0.0000	0.0000	0.0078	0.0054	0.0340	0.0365	0.0203	0.0293	0.5265	0.3402
Sanç D	0.0000	0.0000	0.0304	0.0000	0.0528	0.1236	0.0372	0.0509	0.4447	0.2604
Sanç C	0.0000	0.0000	0.0183	0.0542	0.0701	0.0231	0.0112	0.0456	0.2345	0.5431
Sanç B	0.0000	0.0000	0.0015	0.0658	0.0000	0.0000	0.0000	0.0000	0.7164	0.2163
Mas de Martí	0.0317	0.0328	0.0089	0.0428	0.0335	0.0010	0.0200	0.0185	0.7857	0.0251
Puntal	0.0000	0.0000	0.0017	0.0023	0.0142	0.0000	0.0034	0.0106	0.4614	0.5063
Rompuda	0.0000	0.0000	0.0000	0.0015	0.0011	0.0090	0.0000	0.0054	0.5955	0.3875
Peraire	0.0000	0.0000	0.0017	0.0000	0.0245	0.0066	0.0119	0.0000	0.7932	0.1620
Bastida	0.0000	0.0000	0.0107	0.0087	0.0382	0.0848	0.0191	0.0384	0.7784	0.0216
Matà	0.0558	0.0578	0.0087	0.0229	0.0000	0.0018	0.0000	0.0000	0.6408	0.2124
Cavalls	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6546	0.3454
Josep	0.0000	0.0000	0.0000	0.0000	0.0508	0.0000	0.8378	0.0000	0.1114	0.0000
Llidoner	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6546	0.3454
Mallaeta	0.0000	0.0000	0.0323	0.0233	0.0099	0.0812	0.0252	0.0776	0.4912	0.2592
Estaró	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6546	0.3454
Serretó	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6546	0.3454
Antona	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6546	0.3454
Mas del Viudo	0.0000	0.0000	0.0110	0.0032	0.0000	0.0000	0.0086	0.0098	0.2588	0.7087
Mas del Riu	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6546	0.3454
Clos	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1291	0.8709
Mas del Gat	0.0000	0.0000	0.0080	0.0043	0.0112	0.0008	0.0067	0.0227	0.5655	0.3808
Mas Blanc	0.3797	0.3933	0.0589	0.1557	0.0000	0.0123	0.0000	0.0000	0.0000	0.0000
Sant Joan	0.3750	0.3885	0.0582	0.1539	0.0017	0.0142	0.0004	0.0005	0.0047	0.0028
Canals	0.0000	0.0000	0.0000	0.0000	0.2130	0.4991	0.1127	0.0038	0.0441	0.1274
Mitreres	0.0000	0.0000	0.0000	0.0319	0.1604	0.5094	0.0728	0.1148	0.0285	0.0823

for each period; an assemblage with materials from all 11 periods would have posterior probabilities of 0.09 for each of the periods.

For the surface collections studied here, however, it is apparent that the chronological distributions for most of assemblages are strongly unimodal. A single chronological period strongly dominates every assemblage, even those with the probability of occupation during other periods. One possible explanation for this pattern, especially given the relatively low frequency of projectile elements in many surface collections, is that the range of chronological periods with which an assemblage is associated is a function of the total number of the projectile elements in an assemblage—analogous to the well-known relationship between sample size and diversity (Grayson 1981; Kintigh 1984). In fact, this relationship does seem to account for the diversity of projectile element classes in assemblages. A regression of the number of projectile elements versus the number of projectile classes (Fig. 6) shows that they are correlated (R=0.54, p<<0.05). A single outlier site, Sant Joan, has a point assemblage that contains a large

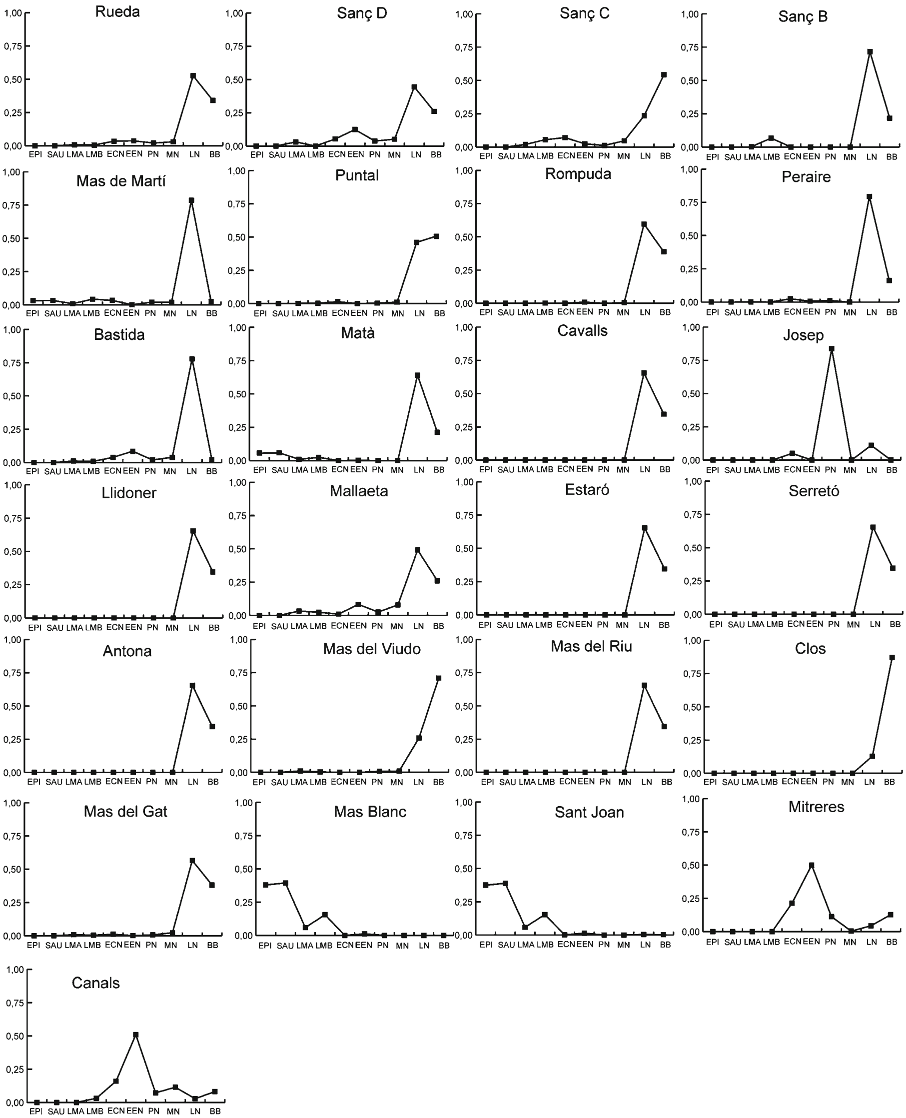

Fig. 5 Surface collections data set. Calculated posterior probabilities that each collection accumulated during each chronological period. Chronological periods shown on the *x*-axis; probability of occurrence in each period shown on the *y*-axis. All graphs are to the same scale

number of backed bladelets. Evidence from other regions indicates that single projectiles were tipped with many more backed bladelets than other forms, leading to their much higher representation in associated assemblages (Myers 1989). Eliminating this single site produces an even stronger correlation between sample size and projectile class diversity (R=0.89, p<<0.05). However, the same relationship is not seen (Fig. 7) when sample size and chronological diversity are compared (R=0.18, p=0.39 for the standard deviation of posterior probability vs. projectile sample size, excluding Sant Joan). For the sites tested here, the Bayesian-derived temporal probabilities appear to be

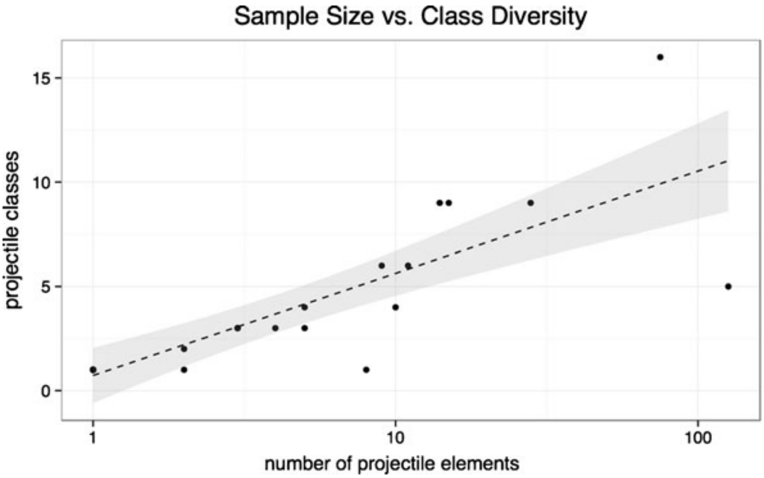

Fig. 6 Linear regression of projectile class diversity vs. projectile sample size for all surface collections

robust to variations in sample size, even though larger sample sizes are certainly desirable. This increases our confidence that the distributions shown in Table 5 and Fig. 5 are reliable estimates of the likelihood that the assemblages date to the time period indicated. This in turn allows us to use these results to examine the occupational history of the Upper Maestrat in the early and middle Holocene.

Figure 8 shows the surface sites grouped according to their posterior probabilities, using a hierarchical cluster analysis. The grouping closely matches the patterning that can be seen visually in the graphs of Fig. 5. The largest group of assemblages are those that exhibit high probabilities of occupation during the Late Neolithic/Chalcolithic. This group of Late Neolithic/Chalcolithic assemblages can be further subdivided into several sites that lack evidence of subsequent occupation in the Bell Beaker period, but

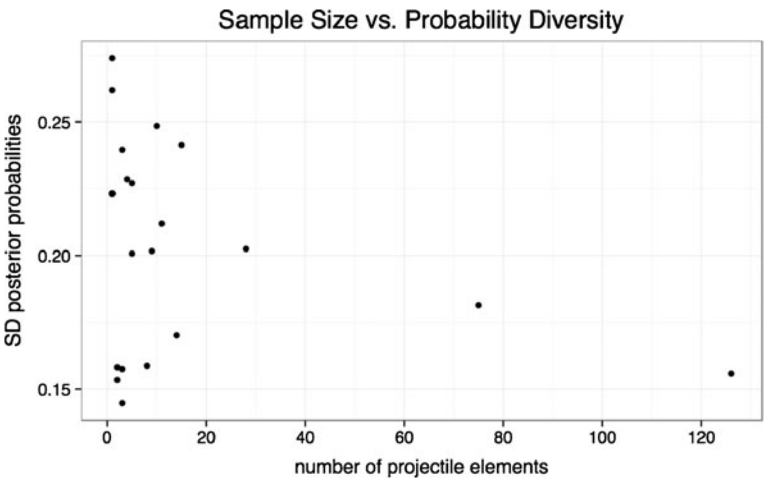

Fig. 7 Linear regression of chronological diversity (measured in standard deviation of posterior probability values) vs. projectile sample size for all surface collections

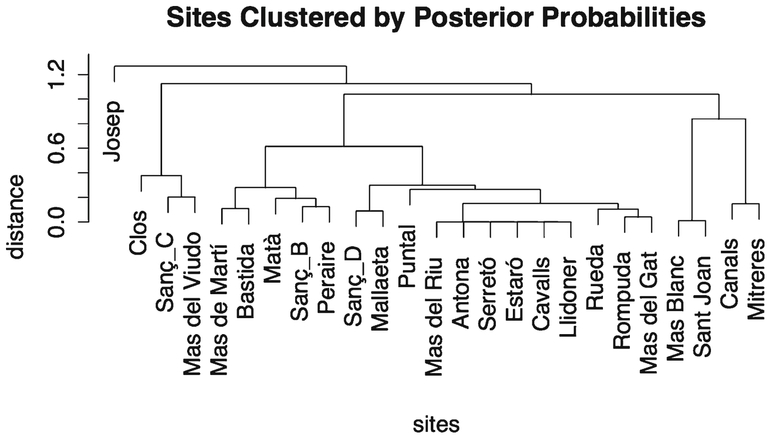

Fig. 8 Hierarchical cluster analysis of surface collection, grouped by posterior probabilities of occupation in each period

which may or may not have low probabilities of earlier occupations (Mas de Martí, Bastida, Matà, Sanç B, and Peraire). The remaining Late Neolithic/Chalcolithic sites exhibit higher probabilities of continuing occupation during the Bell Beaker. Three sites (Clos, Sanç C, and Mas del Viudo) exhibit the highest probabilities of occupation during the Bell Beaker and the five remaining sites show the highest probabilities of occupation in the early to mid-Holocene: Josep in the Middle Neolithic, Canals and Mitreres in the Early Neolithic, and Mas Blanc and Sant Joan in the Epipaleolithic/Mesolithic.

In addition to evidence of higher probability primary occupation, a number of the sites in Fig. 8 show evidence of the possibility of occupation in other periods as well, although in all cases the probabilities of secondary occupations are below 0.16. While this low probability of multiple occupation is difficult to assess on a site-by-site basis,

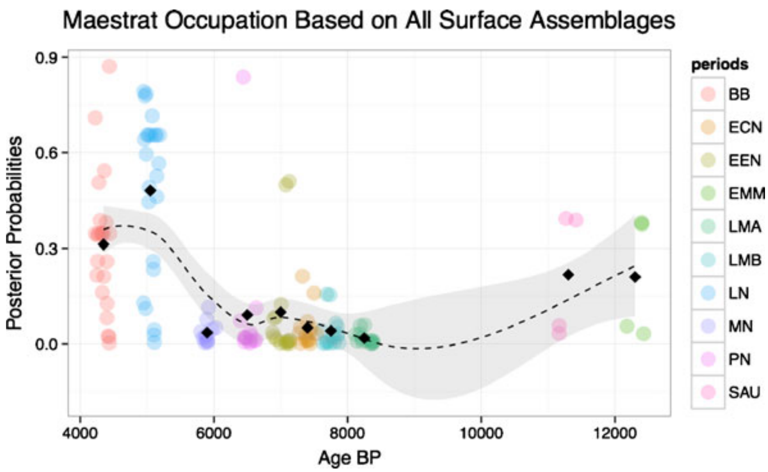

Fig. 9 Bayesian posterior probabilities of occupation during each time period for all surface assemblages. *Dashed line* shows LOESS (Locally Estimated Scatterplot Smoothing) curve fit to the distribution; *shaded area* indicates 95 % confidence interval for LOESS curve. Midpoint of numerical age range is used for each time period (see text and Table 5)

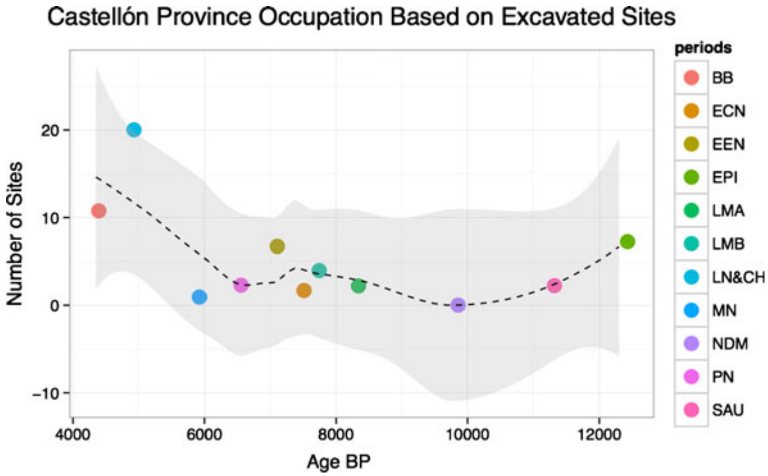

Fig. 10 Number of excavated sites in Castellón Province dated to each time period. *Dashed line* shows LOESS curve fit to the distribution; *shaded area* indicates 95 % confidence interval for LOESS curve. Midpoint of numerical age range is used for each time period (see supplementary materials Table SM4)

combining all probabilities allows us to take a global perspective on the settlement history of the Upper Maestrat. Figure 9 combines the results of the Bayesian analyses and displays them according to the mid-point of each period in calendar years. A LOESS (Local Estimate Scatterplot Smoothing) curve is fit to the distribution, with a 95 % confidence interval in gray.

There is evidence for some amount of terminal Pleistocene or early Holocene occupation, though the temporal indicators do not distinguish among these well, leading to modest maximal probabilities for this time interval. There is no evidence for subsequent occupation of the Upper Maestrat until after 8,000 cal BP—though this may be due to a lack of suitably time-sensitive artifacts as much as a lack of occupation (see above). There is strong evidence that the region was occupied during the Early and Middle Neolithic, but the data suggest that the occupation was very limited. Strong evidence for widespread occupation of the Upper Maestrat first appears with the Late Neolithic and continues into the Bell Beaker period.

This offers a way to evaluate reliability of the Bayesian approach described here. Figure 10 shows the frequency of all excavated sites in the Province of Castellón that are attributed to each of the 11 temporal periods we use here (see supplementary materials Table SM4 for details). It is clear that the frequency distribution of sites through time closely matches the distribution of posterior probabilities of occupation derived from Bayesian probability dating of surface collections. In fact, site frequency through time is highly correlated with the mean Bayesian probability of occupation through time: R=0.94 and p<<0.01.

Conclusion

We presented a probabilistically explicit approach for relative chronology building on lithic surface collections from 13,000 to 4,200 cal BP in eastern Spain. Our approach, based on empirical Bayesian methods, combines prior knowledge derived from chronologically reliable archaeological contexts—expressed in prior probability values—with conditional probability values drawn from undated surface assemblages to produce posterior probability estimates of occupation within 11 different temporal periods.

Our approach, using widely found projectile element forms, is especially valuable for analyzing surface sites that include archaeological materials accumulated during different chronological periods—a very common occurrence. Even though 50 % of projectile classes considered here do not display the ideal unimodal temporal distributions desired for classical seriation techniques, this work has shown that they can be robust markers for chronology building, in spite of varying degrees of temporal uncertainty, if incorporated into a probabilistic framework using Bayesian inference.

Overall, our results are statistically consistent with broad regional-scale observations based on excavated sites. They agree with excavated data that suggest the Middle Neolithic (*ca*. 6,200–5,600 cal BP) is poorly represented in the radiocarbon archaeological record compared with the Early and the Late Neolithic (Bernabeu *et al*. 2008). Additional criteria, such as summed probabilities of calibrated radiocarbon dates at local and regional geographic scales, could provide further insights for testing whether the patterns observed in the surface archaeological record is an outcome of population history dynamics (Shennan 2002; Surovell *et al*. 2009).

In this sense, future contributions can be developed in several ways. This Bayesian approach could be applied to a wider range of artifact materials and technologies, such as ceramics, ground stone, and shell (as was the case for Temporal Index, mentioned above). Application of Bayesian estimation dating to ceramics has given promising results (Ortman *et al*. 2007; Roberts *et al*. 2012). Given the success of Bayesian dating estimates using only chipped stone projectile tips, incorporating a wider range of material culture with different chronological signals may well provide higher dating precision in addition to allowing this method to be used on a larger number of surface assemblages. Another avenue for future work involves exploring the variability of the estimated posterior distribution values by running simulation experiments based on stochastic models such as Markov Chains and Monte Carlo approaches. Finally, Bayesian age estimates for surface assemblages could be combined with GIS spatial analysis techniques, such as Settlement Intensity Index and Artifact Accumulation Rates (Barton *et al*. 1999, 2002), to further investigate diachronic changes in regional-scale land use.

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