



# Unraveling Early Holocene occupation patterns at El Arenal de la Virgen (Alicante, Spain) open-air site: an integrated palimpsest analysis

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## Abstract

Palimpsests are ubiquitous in the open-air archaeological record. Yet, integrated intra-site research strategies of palimpsest dissection to infer occupational histories, spatial behavioural patterns and site formation processes remain scarce in the postglacial archaeology. In this work, we apply an integrated protocol of palimpsest analysis to the Mesolithic Unit IV of El Arenal de la Virgen site, radiocarbon dated in two different occupation phases (9.3–9.1 k and 8.6–8.3 k cal BP). While the archaeostratigraphic analysis identified the absence of sterile layers between both phases, the lithic refits confirmed the good preservation of the spatial properties of the assemblage. Using different point pattern analysis and geostatistical techniques, we further investigate the overall distribution pattern, the spatial correlation between lithic remains and occupation features according to different artefact categories, and the variability of spatial autocorrelation in the frequency of burnt microdebris. Our results suggest a behavioural pattern of different, and spatially recurrent, short-term camp occupation episodes. Built on explicit quantitative and reproducible standards, our research approach can be applied to other open-air sites to conduct comparative studies on open-air occupation patterns. This study underscores the importance of considering the palimpsest as an analytical unit and the need for assessing assemblage integrity and site formation processes through multidisciplinary approaches, to better characterise site occupation dynamics.

**Keywords** Open-air sites · Mesolithic · Palimpsests · Intra-site spatial analysis · Lithic refitting · Iberian Peninsula

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## Introduction

Open-air Mesolithic sites often are challenging for investigating intra-site occupation patterns. Besides topographic features, very often the absence of clear physical boundaries for the campsite and human activity areas condition de cultural and natural deposition processes. Furthermore, when the temporal dimension is considered, this often translates into the creation of spatial palimpsests that are formed by extensive site surface areas resulting from recurrent occupation dynamics (Crombé et al. 2003, 2006; Bailey 2007; Carlson and Bement 2022). In addition, many post-depositional disturbance processes by sediment accretion (e.g. colluvial, alluvial and aeolian), erosion (e.g. surface dynamics, deflation) or soil formation can be particularly acute in these open environments.

Yet, very few sites provide exceptionally preserved archaeological contexts with sufficient stratigraphic resolution to enable the interpretation of the spatial distribution of artefacts and other associated features according to

ethnographic site structure models (Yellen 1977; Binford 1978a; O'Connell 1987; Kroll and Price 1991). The open-air Upper Palaeolithic sites in the Paris Basin such as Pincevent (Leroi-Gourhan and Brézillon 1966, 1972), Verberie (Audouze et al. 1981) or Étiolles (Pigeot 1987; Olive 1988) are examples of such sites. Their intra-site spatial distribution studies are considered epitomes of palaeoethnographic archaeological interpretation.

Nevertheless, they are still amenable to post-depositional disturbance processes, and not even such exceptionally well-preserved occupation surfaces necessarily correspond to single occupational episodes, but to palimpsests (e.g. Julien et al. 1992; Audouze and Enloe 1997; Ketterer et al. 2004; Olive 2005). This thwarts any straightforward interpretation of the archaeological layers as living floors in an ethnoarchaeological analogy (Schiffér 1985; Dibble et al. 1997). Addressing the intra-site spatial and temporal dimensions of archaeological site formation, drawing from the palimpsest conception, would ultimately allow to properly define site structure and occupation dynamics (i.e. discriminating long/short occupation time, residential/task specific locations or aggregation/band camps) (Crombé et al. 2006; Vandendriessche et al. 2022; Crawford et al. 2023).

The postglacial archaeological record can offer an extraordinary opportunity to improve our understanding of the relationship between site structure, site function and occupation length on open-air sites. A key issue is that the preservation state of organic materials is often sufficient to yield radiocarbon datasets with enough resolution to build robust chronologies, involving internal phasing and Bayesian chronological modelling for addressing intra-site spatio-temporal dynamics (Crombé et al. 2006, 2013; Wicks and Mithen 2014; Blockley et al. 2018; Vandendriessche et al. 2022; Fernández-López de Pablo et al. 2023).

In this work, we present the results of an integrated palimpsest analysis aimed at characterising the Mesolithic occupation dynamics at the open-air site of El Arenal de la Virgen (Alicante, Spain), setting out an exhaustive, quantitative and reproducible approach. Relying on a comprehensive chronological framework (Fernández-López de Pablo et al. 2023) and geomorphological and micromorphological data (Polo-Díaz et al. 2023), we used archaeostratigraphic and lithic refit analyses to assess the stratigraphic integrity and postdepositional disturbance of the Mesolithic Unit IV, and applied a comprehensive intra-site spatial analysis to establish the association between lithic assemblages and occupation features and scrutinise traces of palimpsest formation.

We discuss how this case study illustrates the potential of this kind of integrated approaches to understand site formation processes, to better characterise occupation dynamics, and to reach a deeper understanding of settlement patterns. Finally, we frame this work within the context of Iberian postglacial archaeology, where current knowledge about

Early Holocene occupation patterns suggests that caves and rockshelters may be overrepresented compared to open-air contexts, possibly due to the confluence of preservation and research biases (Alday 2006; Utrilla and Montes 2009; Gallego-Lletjós 2013; Fernández-López de Pablo et al. 2015; Gameiro et al. 2020; Rabuñal 2021).

## El Arenal de la Virgen

### Location and site description

El Arenal de la Virgen is an open-air site located in the Villena Basin, in the Alto Vinalopó valley (SE Iberian Peninsula). The Villena Basin consists of a broad depression that occupies a NW-SE natural corridor, surrounded by calcareous formations, 80 km away from today's Mediterranean coast and at 500 m.a.s.l (Fig. 1a). It is characterised by the occurrence of endorheic lagoons and ponds, dominated by the now drained Villena Lagoon (Ferrer and Fumanal 1997; Matarredona et al. 2006), and by the formation of sand deposits and continental dunes as a result of late Pleistocene and Holocene intense aeolian activity (Casquel et al. 1989; Ferrer and Fumanal 1997).

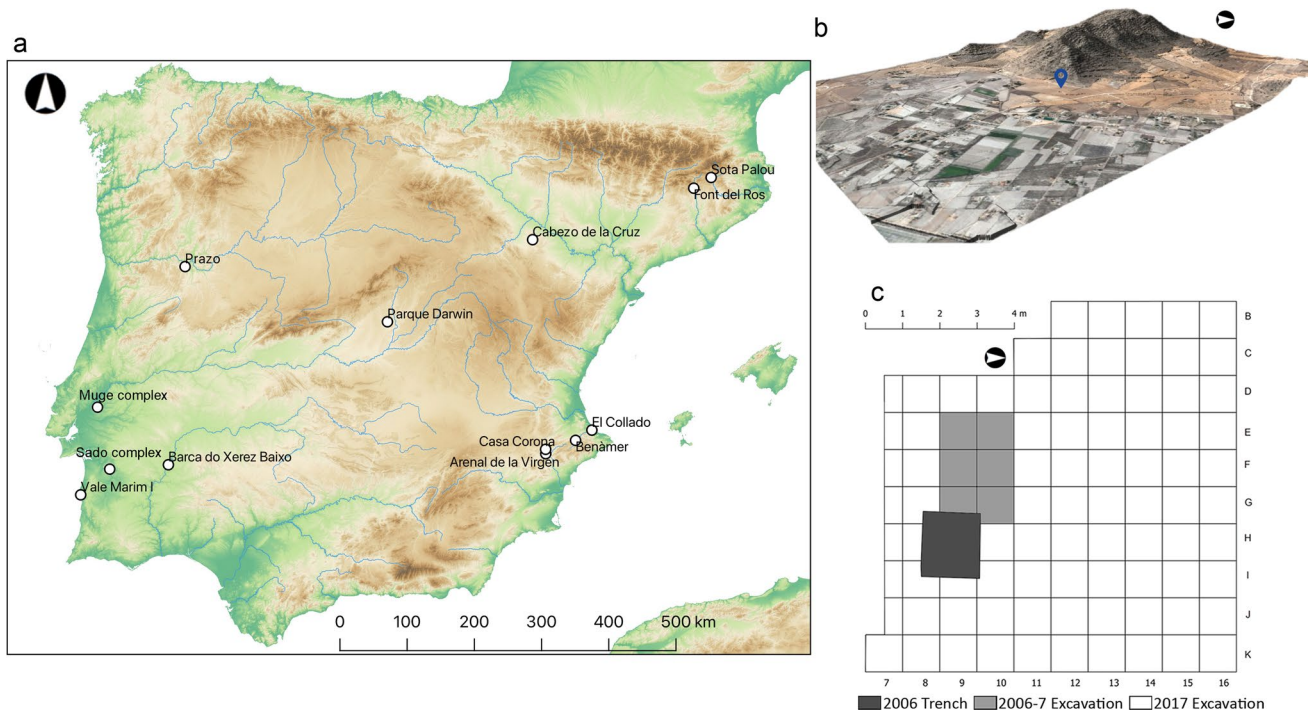
The site is located in a small glaciais of EW orientation, at the foothills of the Castellar mountains and in the southwestern margin of the Villena palaeolake (Fig. 1b). It was discovered in the early 1960s by José María Soler as a surface scatter of lithic and ceramic materials, and attributed to the Early Cardial Neolithic (Soler 1965; Fortea 1973), but it was not excavated until the early 2000s. Over three different seasons in 2006, 2007 and 2017, fieldworks were conducted in an area of 84 m<sup>2</sup> (Fig. 1c) (Fernández-López de Pablo et al. 2008, 2011a, 2023).

### Stratigraphy

The stratigraphic sequence described after the 2017 open-area excavation broadly corresponds to that defined after the earlier works at the site (Fernández-López de Pablo et al. 2023). Five main sandy deposits were documented (Fig. 2): the base unit (V) and the two upper units (I and II) are archaeologically sterile, while the middle units (III and IV) contain a variety of archaeological evidence from the Neolithic and Mesolithic periods, respectively.

Unit III is a 20–25-cm-thick, orange-coloured deposit formed by aeolian and colluvial processes under arid conditions. Two isolated archaeological structures were documented in its upper section: a circular pavement (SU 627) and a shallow pit (SU 620), both in the SE section of the excavated area and without any associated material culture.

In contrast, Unit IV is 40-cm-thick and grey-brownish in colour deposit consisting mainly of edaphised sands, which



**Fig. 1** Map of the Iberian Peninsula with the location of El Arenal de la Virgen and the main open-air Mesolithic sites discussed in the text (a). Location of the El Arenal de la Virgen between the foothills of the Castellar mountains and the Villena Lagoon (modified from

(Fernández-López de Pablo et al. 2008; Fig. 1.C)) (b). Site plan and excavation grid, showing the different areas excavated over the different fieldwork campaigns (c)

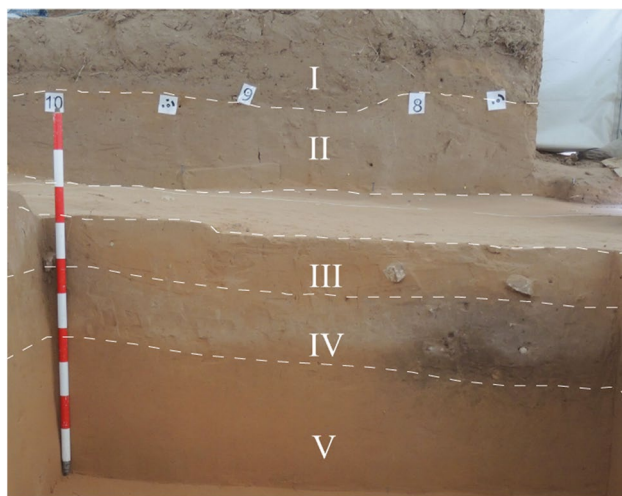
concentrates most of the archaeological evidence as lithic scatters and occupational features.

The contact between both Units shows a clear sedimentary discontinuity, but with some lateral variations. While it is gradual and diffuse in the SE sector, in the NE and

W sections, the impact of aeolian and colluvial processes involved in the accumulation of Units III and II translated into an erosive contact, affecting their preservation in some areas (Polo-Díaz et al. 2023; Fernández-López de Pablo et al. 2023).

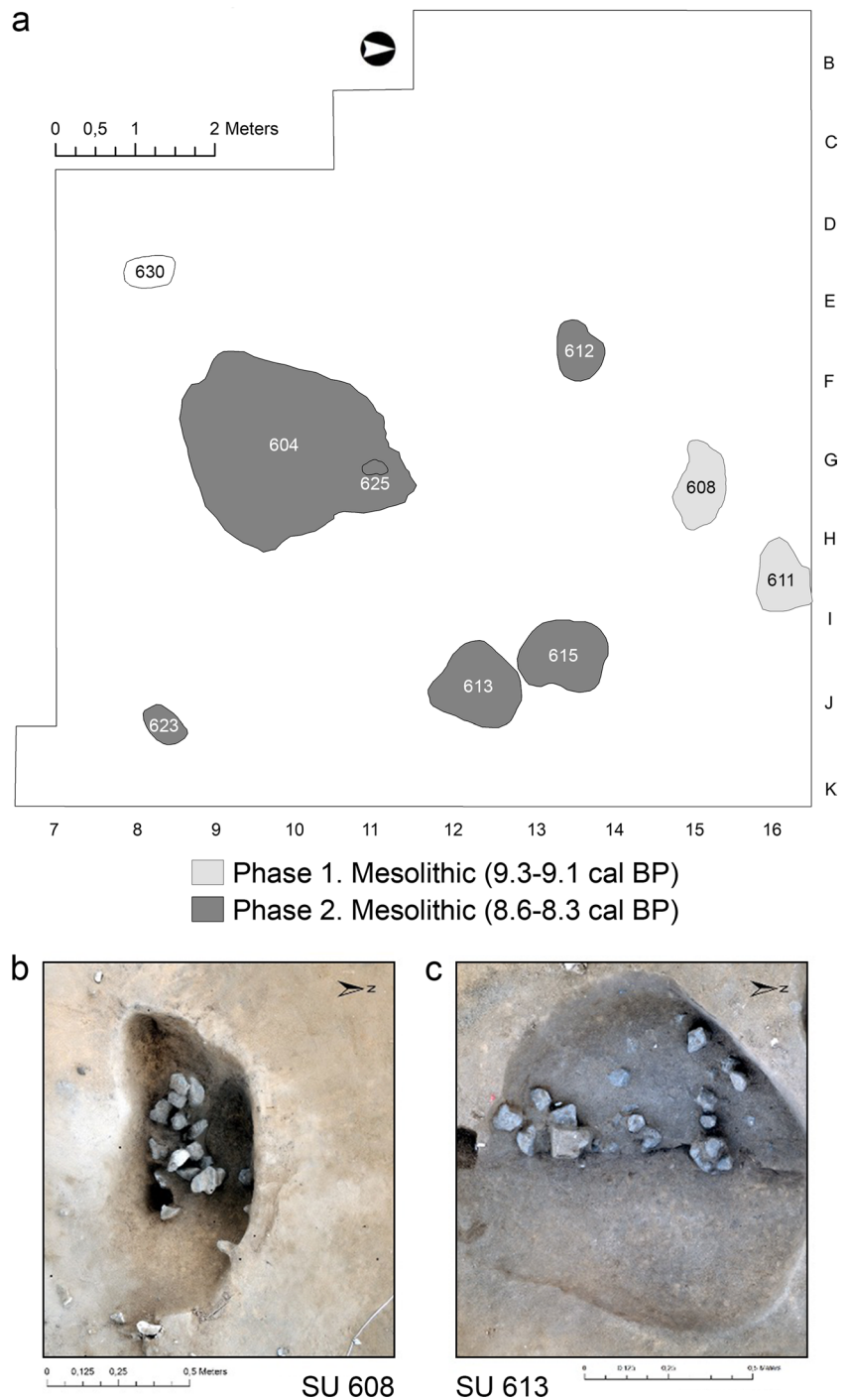
**Archaeological features and chronological framework**

The main evidence of human occupation in Unit IV consists of combustion structures (Fig. 3), corresponding with three hearth-pits (SU 615, 613 and 608) and two surface hearths (SU 623 and 630). We also find two shallow pits (SU 611 and 612) that differ from the previously mentioned hearth-pits in that they are smaller and do not present burnt clasts in their fill. Both however contain abundant charcoal. Lastly, SU 604 was partially excavated during the 2006–2007 fieldworks and preliminarily interpreted as a combustion structure (Fernández-López de Pablo et al. 2011a). However, the 2017 excavation allowed to document the spatial continuity of this feature, describing a sub-circular plan of about 5 m<sup>2</sup> (3 × 2.35 m) and a depth of 0.25 m. This, together with the documentation of a small pit within its perimeter (SU 625), and with a 40 cm vertical limestone block in vertical position, led to its reinterpretation as a disturbed dwelling structure with a peripheral wedge (Fernández-López de Pablo



**Fig. 2** Close-up of the southern end of the East section (grid columns 8–9, rows I–K), indicating the stratigraphic sequence documented in the profile from bottom to top: Unit V, Unit IV, Unit III, Unit II and Unit I

**Fig. 3** Site plan with the location of the archaeological features of Unit IV and their correspondent occupation phase (a), orthophotography of SU 608 (b) and SU 613 (c)



et al. 2023). A detailed description of the archaeological features and their formation processes is provided elsewhere (Polo-Díaz et al. 2023).

The radiocarbon record of El Arenal de la Virgen is composed by 15 AMS  $^{14}\text{C}$  dates from charred vegetal remains recovered inside different features and from occupation levels of Units IV and III (Table 1). A chronological Bayesian phase model (Fernández-López de Pablo et al. 2023) has allowed to model the stratigraphic sequence in three

different phases arranged in sequential order, and establish the chronological boundaries and the occupation span of each phase.

For the analytical purposes of the present study, we are interested in Phase 1 (9247–9041 cal BP) and Phase 2 (8430–8268 cal BP), both associated to Unit IV. Phase 1 is associated with SU 608 and 611, located in the northern section of the excavation area. For its part, Phase 2 is associated with SSUU 604, 612, 613, 615, 623 and 625, covering



**Table 1** Radiocarbon record and calibrated  $^{14}\text{C}$  dates (unmodelled posterior distribution) from El Arenal de la Virgen archaeological sequence. Calibration was performed with OxCal 4.4 (Bronk Ramsey 2009) using the IntCal20 atmospheric curve (Reimer et al. 2020) (modified from Fernández-López de Pablo et al. 2023, Table 1)

| Unit | Phase | SU/spit       | Z       | Sample                       | Lab. ref.   | $^{14}\text{C}$ BP age | $^{13}\text{C}$ | Cal a BP  |
|------|-------|---------------|---------|------------------------------|-------------|------------------------|-----------------|-----------|
| IV   | 1     | 608/3         | 180–172 | <i>Quercus</i> sp. evergreen | Beta-493220 | 8220 $\pm$ 30          | – 27.9          | 9394–9027 |
| IV   | 1     | 611           | 170     | <i>Quercus</i> sp. evergreen | Beta-473942 | 8200 $\pm$ 30          | – 26.4          | 9275–9026 |
| IV   | 2     | 625           | 217     | <i>Quercus</i> sp. evergreen | Beta-473944 | 7850 $\pm$ 30          | – 25.5          | 8765–8546 |
| IV   | 2     | 613/1         | 184–187 | <i>Quercus</i> sp. evergreen | Beta-493221 | 7820 $\pm$ 30          | – 25.4          | 8698–8520 |
| IV   | 2     | Level 4/ top2 | 180–172 | <i>Quercus</i> sp. evergreen | Beta-493228 | 7790 $\pm$ 30          | – 25.8          | 8636–8458 |
| IV   | 2     | 613/1         | 194–190 | <i>Quercus</i> sp. evergreen | Beta-493225 | 7770 $\pm$ 30          | – 25.8          | 8600–8449 |
| IV   | 2     | 604           | 217     | <i>Quercus</i> sp. evergreen | Beta-243772 | 7750 $\pm$ 40          | – 25.8          | 8595–8426 |
| IV   | 2     | 623/1         | 215     | <i>Quercus</i> sp. evergreen | Beta-493223 | 7750 $\pm$ 30          | – 26.6          | 8594–8430 |
| IV   | 2     | 608/1         | 166–161 | <i>Quercus</i> sp. evergreen | Beta-493219 | 7700 $\pm$ 30          | – 23.7          | 8547–8411 |
| IV   | 2     | 612           | 187–194 | <i>Quercus</i> sp. evergreen | Beta-502077 | 7680 $\pm$ 30          | – 26.6          | 8541–8407 |
| IV   | 2     | 613/2         | 193–187 | <i>Pinus</i> cone scale      | Beta-493222 | 7660 $\pm$ 30          | – 28.1          | 8536–8389 |
| IV   | 2     | 604/4         | 220–216 | <i>Pinus</i> cone scale      | Beta-493226 | 7550 $\pm$ 40          | -               | 8420–8210 |
| IV   | 2     | 615           | 191     | Conifer                      | Beta-493224 | 7480 $\pm$ 30          | -               | 8371–8195 |
| IV   | 2     | Level 4/top1  | 171–168 | Conifer                      | Beta-493227 | 7470 $\pm$ 30          | – 23.2          | 8365–8193 |
| III  | 3     | 620           | 205     | <i>Quercus</i> sp. evergreen | Beta-473943 | 6560 $\pm$ 30          | – 26.0          | 7560–7425 |

most of the excavation area. According to the most restricted chronological model, based on short-lived samples, both phases present short duration spans (0–168 and 0–180 years respectively at 95.4% CI), and between them there is a chronological hiatus, of an erosive nature, of 68–625 years (95.4% CI). The end of the Mesolithic occupation of the site coincides with the deposition of Unit III, associated to the 8.2 kya cal BP event, and represents an occupation hiatus until the Early Neolithic (Fernández-López de Pablo et al. 2023).

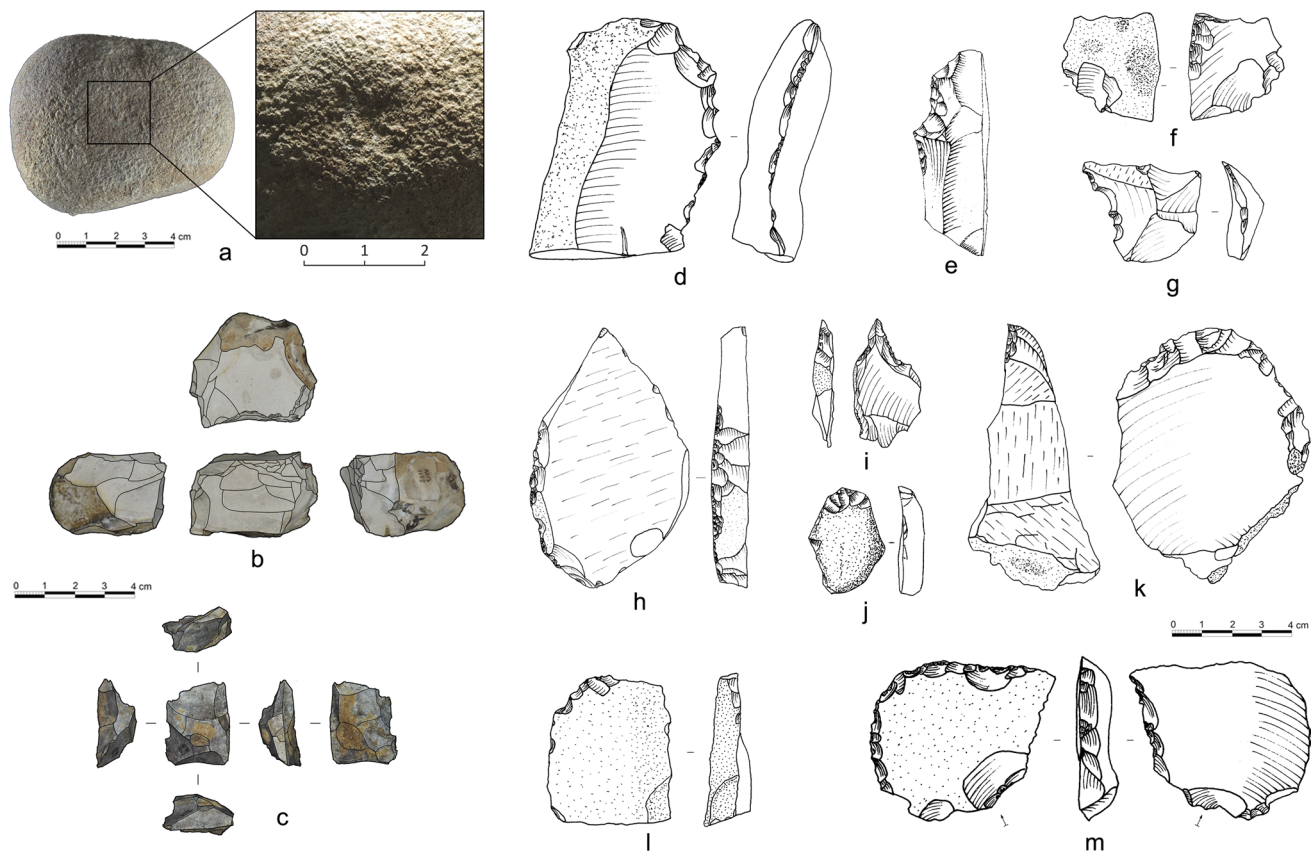
### Lithic assemblage

The lithic assemblage totals 2106 remains. Chert from local sources (Fernández-López de Pablo et al. 2011a; Soto 2016) is almost the only raw material selected for knapping (99.34%), while quartzite, sandstone and limestone are very scarce and appear in the form of fragments, hammers, flakes, slabs or pitted cobbles (Fig. 4a). The morpho-technical analysis of the assemblage shows the predominance of flake production strategies (Fig. 4b, c), scarcely standardised tool configuration and a rather limited typological diversity, notably dominated by notches and denticulates some of machrolithic character (Fig. 4d–m) (Rabuñal 2021). These techno-typological characteristics are consistent with the expedient technological context of the variable and polythetic technocomplex Notched and Denticulated Mesolithic (Aura 2001; Alday 2002, 2006; Cava 2004; Vaquero 2004; Vaquero et al. 2009; Aura et al. 2006; Vaquero et al. 2006; Martínez-Moreno et al. 2007; Montes 2007; Soto et al. 2016).

### Materials and methods

In this work, we addressed Unit IV of El Arenal de la Virgen site as an analytical unit, developing a reproducible top-down research strategy aimed at reconstructing site formation processes and understanding the occupation palimpsest (Fig. 5). For this study, we considered the spatial information of the complete lithic assemblage recovered in Unit IV, as well as that of the occupation features (considering both their outline and centroid) (“**Fieldwork methods**”). We evaluated the internal diachrony of the occupation and the potential preservation of different sub-layers and occupation phases through the analysis of the vertical distribution of the lithic remains (“**Archaeostratigraphy**”), coupled with the information provided by a comprehensive chronological framework (“**Archaeological features and chronological framework**”) (Fernández-López de Pablo et al. 2023). Palimpsest formation and site structure were investigated relying on the taphonomic and behavioural information provided by lithic refitting (“**Lithic refitting**”), and on a comprehensive intra-site spatial distribution analysis aimed at characterizing the distribution patterns of lithic remains and establishing their association with occupation features (“**Spatial analysis**”).

Unfortunately, the lack of bone preservation impeded the integration of this proxy in the intra-site spatial distribution analysis. Also, the widespread surface patination of the lithic remains, with 93.27% of the collection fully or partially patinated, prevented the study of the spatial distribution of Raw Material Units (Roebroeks 1988; Vaquero 2008).



**Fig. 4** Lithic remains from El Arenal de la Virgen: sandstone pitted-cobble (a); multifacial multipolar core on prismatic blank (b); bifacial centripetal—discoïd—core (c); denticulates (d–g); abrupt (h); borer (i); endscrapers (j, k); scrapers (l, m)

## Fieldwork methods

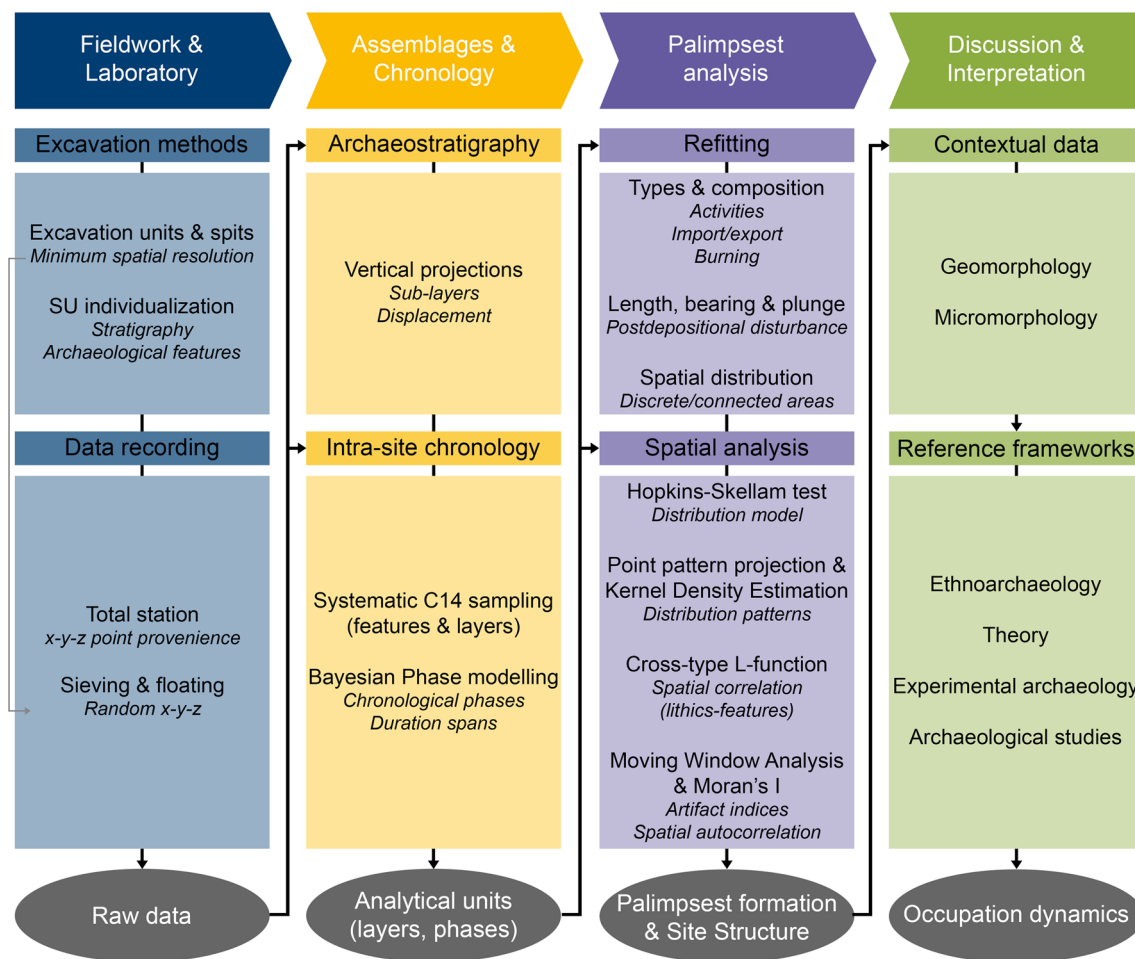
A high-resolution excavation and data recording strategy was implemented throughout the different excavation campaigns. The sedimentary units (Unit) and archaeological features (SU)—both hearth-pits and unstructured concentrations of lithics and burnt clasts—were independently recorded and excavated following field observations and stratigraphic standards (Harris 1989). The deposits were manually excavated in 5 cm artificial spits, following the strata dip. The excavation area was structured in 1 m<sup>2</sup> excavation units, each divided into four 0.5 × 0.5 m subunits. The sediments were dry sieved on site through 5 and 2 mm meshes. Sediment samples (10 l per excavation unit and spit) and the fill of the archaeological features were wet sieved using the same mesh sizes and floated.

To perform the spatial registration, the location of each finding (archaeological remains and features) was three-dimensionally recorded using the ARCH-e System Fieldwork (Canals et al. 2008; Canals and Guerra 2011), a wireless data recording network that integrates a robotic total station (Trimble S8) and PDA terminals with a server containing the centralised data repository. Random x-y-z coordinates were

produced in Microsoft Excel (Supplementary Information S11.1) for every sieve find, as well as for the 2006 and 2007 fieldwork materials, based on the spatial information of their corresponding excavation subunit and spit (0.5 × 0.5 × 0.05 m) which provides enough spatial resolution for not affecting the distribution patterns (Gilead 2002). Of the 2106 lithic remains studied, 870 were point provenience recorded in the field using the total station, while random spatial information was produced for the 1236 sieve finds.

## Archaeostratigraphy

During the excavation, the first recorded lithic remains appeared on the boundary between the lower section of Unit III and Unit IV, but we could not detect any discontinuity in the distribution of the materials through the excavation of Units III and IV. In order to analyse the vertical distribution of the lithic remains and evaluate the presence of different archaeological layers separated by sterile hiatuses, we conducted an archaeostratigraphic analysis (Canals 1993; Canals et al. 2003; Martínez-Moreno et al. 2016; Sánchez-Romero et al. 2017) of the complete lithic assemblage—including the sieve finds. This entailed the study of the



**Fig. 5** Schematic representation of the analytical workflow developed in this study of El Arenal de la Virgen Unit IV

vertical distribution of the lithic remains throughout the entire excavation area by examining sequential longitudinal and cross-section vertical projections, produced with the GIS software QGIS Desktop 2.18.6 (QGIS.org 2018). The vertical projections are 50 cm wide, since this is the minimal reliable spatial resolution allowed by the excavation and data recording methods for the random coordinates of the sieve finds. Thus, a total of 40 vertical projections (20 N-S and 20 E-W) were examined.

### Lithic refitting

For this study, one of the authors (JRR) devoted around 160 h (approximately a month's work over different periods) to develop the lithic refitting analysis. No size threshold was established for the analysis, although the patinated microdebris ( $n = 1000$ ) were excluded.

Three types of connections were established based on different proposals (Cziesla 1990; Petraglia 2002; Vaquero et al. 2007; Sisk and Shea 2008; López-Ortega et al. 2011)

as well as on the characteristics and objectives of this case study:

- Technical refit: connections derived from intentional conchoidal fracture, that is, from an action related to knapping or retouching. This type includes refits between two flakes (dorso-ventral connection), between a flake and the core from which it was detached (flake-core connection), between a retouch flake and the configured blank (retouching connection), and between the fragments of an intentionally fractured item (intentional fracturing connection).
- Conjoin: connections derived from unintentional non-conchoidal fractures (e.g. between the fragments of a broken flake). This type includes longitudinal Siret type fractures (Cziesla 1990), although they should be considered with caution since this is a diagnostic knapping accidental break (Inizan et al. 1999). Thus, from a behavioural perspective, they might as well be related to technical refits.

- Thermal conjoin: connections derived from thermal alteration, including between two fragments broken by fire alteration and between a potlid fracture and the blank from which it was detached.

Based on the spatial information of the remains and the sequence order of each refit group, connection lines and connection distances were automatically produced using the “Points to path” tool in QGIS. When it was not possible to establish a sequence order (e.g. a conjoin of several fragments of the same item), we used a proximity criterion. To study the connection distances, in addition to descriptive statistics (maximum, minimum, mean, median, SD), we categorised them as short (< 0.5 m), medium (0.5–2 m), long (2–4 m) and very long (> 4 m) connections (Cziesla 1990).

After this, we recorded each connection line’s bearing (orientation angle relative to the north (0–180°)) and plunge (angle relative to the horizontal plane (0–90°)) (McPherron 2005; Sisk and Shea 2008; de la Torre et al. 2014, 2019; López-Ortega et al. 2019). Bearings were automatically calculated on QGIS with the *main\_angle* function, while angles of plunge were calculated through trigonometry taking into account the plunge direction (for the case of angles of plunge only these connection lines where both elements were spatially recorded with total station were considered, excluding those with random coordinates). To study the orientation patterns of connection lines, we produced a Rose diagram for connections longer than 0.5 m using the full circle strike diagram of the GeoRose software (version 0.5.1).

## Spatial analysis

For the intra-site spatial distribution analysis of the lithic assemblage, we applied different geostatistical and point pattern analysis methods (Table 2). The objective was to characterise the distribution model of the lithic remains, visualise the distribution pattern of the assemblage and specific artifact categories, contrast the spatial correlation between lithic remains and occupation features, and analyse the spatial variation and autocorrelation of indices of artifact representation (Hodder and Orton 1976; Wheatley and

Gillings 2002; Baddeley et al. 2015; Bevan 2020; Gillings et al. 2020).

First, to characterise the distribution model of the lithic remains, we computed the Hopkins-Skellam test (Hopkins and Skellam 1954; Domínguez-Rodrigo et al. 2018; Saladié et al. 2021; Díaz-Rodríguez and Fábregas-Valcarce 2022). This test computes the ratio of the mean squares of the nearest-neighbour and the empty-space distances (aggregation coefficient “A”) and compares it to the F function of continuous probability distribution for statistical significance. A random distribution pattern produces an  $A = 1$ , while  $A > 1$  indicates a regular distribution and  $A < 1$  a clustered distribution pattern. We selected the Hopkins-Skellam test because it is less sensitive to edge effect bias and spatial inhomogeneity than other aggregation tests such as the Clark-Evans test (Baddeley et al. 2015).

Next, to visualise the variation of the distribution patterns of the lithic remains and artifact categories, we produced point pattern projections and raster density maps through the kernel density estimation (KDE) (Hodder and Orton 1976; Diggle 1985; Baxter et al. 1997; Romagnoli and Vaquero 2016; Bevan 2020; Sánchez-Romero et al. 2022). We selected a 0.28 m bandwidth—equivalent to a search radius 0.56 m—for all the kernel density maps, which allows to compute a density estimation for a 1 m<sup>2</sup> circular surface around each point. We applied the Jones-Diggle edge-effect correction, a normalised corrected estimator with a better performance than other options available (Baddeley et al. 2015).

Along with the complete lithic assemblage, we analysed the spatial distribution of burnt remains, microdebris (less than 10 mm of maximum dimension, representing 51.14% of the assemblage) and large remains (over 30 mm of maximum dimension, representing the larger 7.8% of the assemblage).

The spatial distribution of burnt lithics—whether the burning is contemporaneous or posterior to their deposition—and their relationship with the preserved combustion structures can help to answer relevant questions, such as the integrity of the lithic assemblage or the identification and spatial distribution of non-preserved combustion areas (latent hearths or phantom hearths) (Leroi-Gourhan and

**Table 2** Summary of the objectives and methods applied in the intra-site spatial analysis of the El Arenal de la Virgen lithic assemblage

| Goal   | Methods   | References   |
|--|---|--|
| Quantitative characterisation of the distribution model                                    | Hopkins-Skellam test  | (Hopkins and Skellam 1954)   |
| Visualisation of the distribution pattern of the lithic assemblage and artifact categories | Projections of the point pattern<br>Kernel density estimation (KDE) | (Hodder and Orton 1976; Baddeley et al. 2015)<br>(Diggle 1985; Baxter et al. 1997) |
| Spatial correlation between lithic remains and occupation features                         | Cross-type L-function   | (Baddeley, Rubak and Turner 2015; Brunsdon and Comber 2019)                        |
| Variability and spatial autocorrelation of artifact representation indices                 | Moving Window Analysis<br>Global and Local Moran’s <i>I</i>         | (Hagen-Zanker 2016; Reeves et al. 2019)<br>(Anselin 1995; Reeves et al. 2019)      |



Brézillon 1972; Petraglia 2002; Sergant et al. 2006; Alpersen-Afil et al. 2009; Alpersen-Afil 2012, 2017; Aldeias et al. 2016; Aldeias 2017; Sánchez-Romero et al. 2020). We considered the presence of thermal alteration based on the identification of crazing, fractures and/or potlid fractures, which are considered diagnostic features linked to severe thermal impact (Patterson 1995; Sergant et al. 2006; Alpersen-Afil 2012). Thermal alteration was documented in 20.53% of the lithic remains.

Microremains are an essential component of spatial analyses. Because they are sensitive to the size-sorting effects of certain post-depositional processes (Schick 1986; Schiffer 1987), their presence and distribution pattern can provide information about the integrity of the spatial distribution pattern. From a behavioural perspective, they are a key archaeological indicator of hearth-related activity areas (Brooks and Yellen 1987; O'Connell 1987; Stevenson 1991; Vaquero and Pastó 2001). Indeed, according to Binford's refuse disposal model, they constitute the main form of primary refuse deposited in the immediate surroundings of the hearth shaping the drop zones (Binford 1978a).

Contrary to small elements that tend to remain in the place of primary refuse, and specially in sandy substrates, the larger refuse can be dropped in situ, tossed into the hearth, or tossed away forming peripheral deposition areas—the toss zones in Binford's model (Binford 1978a). In addition, these larger elements are more susceptible to anthropic displacement, whether unintentional (scuffage) or intentional (refuse management into secondary refuse areas, or dumps) (Binford 1978a; Brooks and Yellen 1987; O'Connell 1987; Fisher and Strickland 1989; Stevenson 1991).

Moreover, these distribution analyses were complemented with categorised point projections of knapping elements (cores and core fragments, hammers and hammer fragments, and manuports) and retouched artifacts. The aim was to evaluate and discuss their relationship with the location and characteristics of the activity areas.

In addition to the visual inspection of the spatial distribution, and to quantitatively test the spatial correlation between lithic remains and occupation features, we implemented the Cross-type L-function (Domínguez-Rodrigo and Cobo-Sánchez 2017; Brunsdon and Comber 2019; Saladié et al. 2021). This function analyses the spatial dependence or independence between two types of points in a pattern, calculating the expected number of  $j$  points (here, lithic remains) at a certain distance of an  $i$  point (here, the centroid of the occupation features). The acceptance region of spatial randomness is produced by Monte Carlo simulations of random type assignment to the points in the pattern, maintaining their proportion (here, 99 simulations). An empirical function above the acceptance region indicates spatial attraction of the type  $j$  points regarding the type  $i$  points, whereas

a function below the acceptance region indicates inhibition or repulsion.

Finally, to deepen the quantitative analysis of the spatial distribution of the lithic remains and analyse the palimpsest formation and the site structure of the Unit IV of El Arenal de la Virgen, we followed and adapted the analytical protocol proposed by Reeves and colleagues (Reeves et al. 2019) to analyse discard patterns in time-averaged deposits by studying the spatial variation and autocorrelation of analytical indices. Built on the recent chronological phasing work of Unit IV (Fernández-López de Pablo et al. 2023) and the refit analyses presented here, we aim to deepen into the relationship between site structure and palimpsest formation.

Following this protocol, the first step is to calculate designed indices or ratios of representation of material categories (either materials, taphonomic features, size categories, lithic types, faunal anatomical parts...) for a determined neighbourhood around each point—hereafter artifact indices—through a Moving Window Analysis (Hagen-Zanker 2016). This way, each point in the pattern is assigned a value resulting from the calculation of the computed index, allowing to visualise the spatial variation of the given index through projections of the point pattern (Reeves et al. 2019). A key advantage of this Moving Window approach is that it allows to calculate the indices and evaluate their spatial variation in a non-partitive way, contrary to other more straightforward approaches such as a quadrat count based on arbitrary spatial units—e.g. the excavation grid (Wandsnider 1996).

Combining the rationale of the importance of both microdebris and burnt lithics to characterise site formation processes and site structure, we computed the burnt microdebris index. This index is calculated by dividing the number of burnt microdebris by the total number of microdebris within the given neighbourhood (Burnt Microdebris Index = burnt microdebris/total microdebris). In this case, we determined a circular window with a 0.56 m radius, delimiting a 1 m<sup>2</sup> circular neighborhood. This way, the index result could be expressed as the ratio of burnt microdebris per square meter.

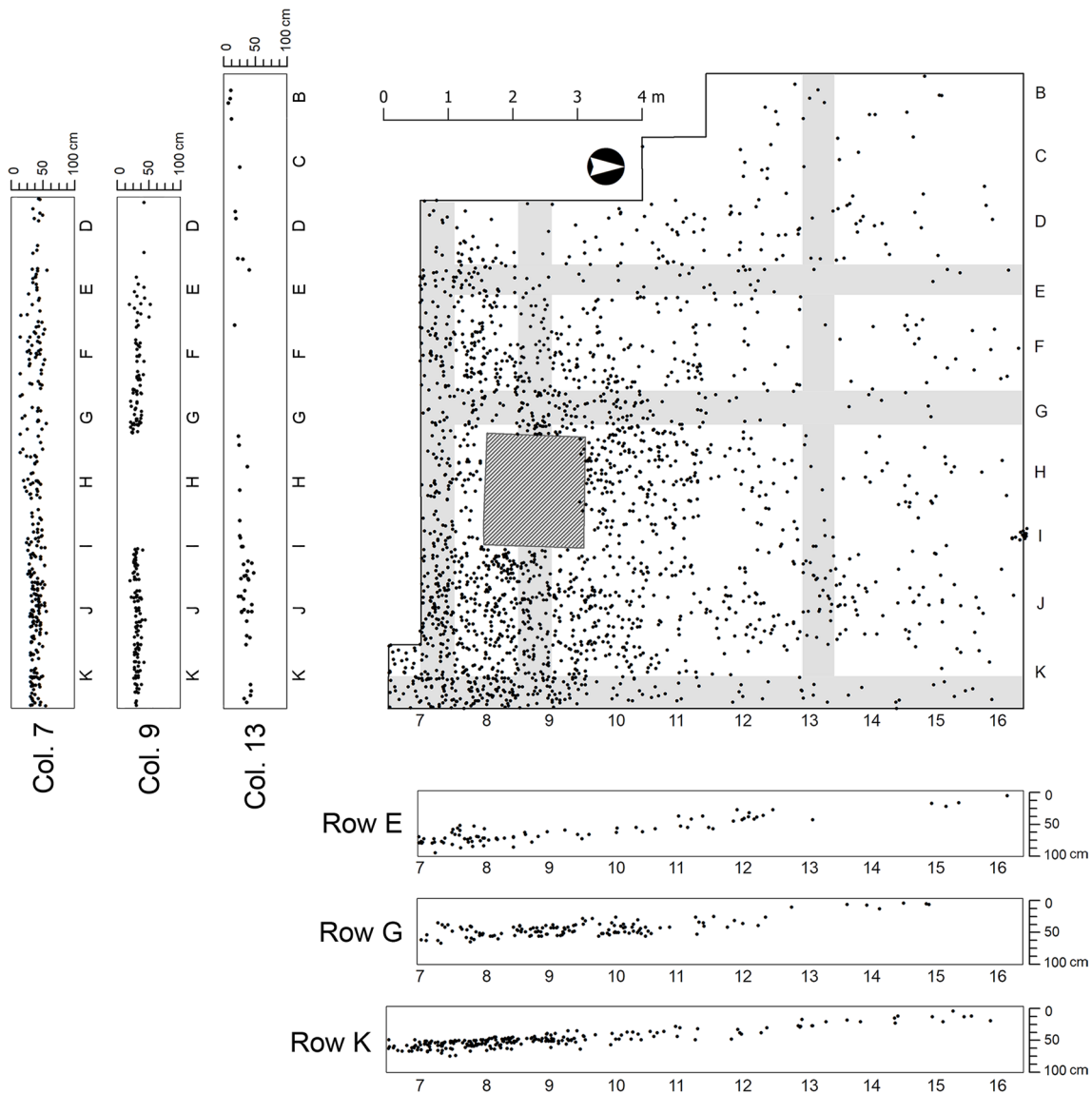
The statistical significance of the indices' spatial variation was then calculated by means of the Global and Local Moran's  $I$  tests of spatial autocorrelation (See Supplementary Information S11.2 for further details) (Anselin 1995; Bivand et al. 2013; Reeves et al. 2019; Sánchez-Romero et al. 2020, 2021, 2022). This procedure allows to detect statistically significant concentrations of similar values within the neighbourhood of each observation, classifying each one as a significant cluster of high values (when  $Z \geq 1.96$  and variance > mean(variance)), a significant cluster of low values (when  $Z \leq -1.96$  and variance < mean(variance)) or non-significant location (Reeves et al. 2019).

The analytical and statistical protocols applied for this study were implemented in QGIS (QGIS.org 2018) and in R (version 3.6.3) (R Core Team 2020), with the packages “spatstat” (Baddeley and Turner 2005), “rgeos” (Bivand and Rundel 2018), “sp” (Bivand et al. 2013), “spdep” (Bivand et al. 2013) and “dbscan” (Hahsler et al. 2019). To enable the reproducibility and replicability of this study (Marwick 2017), the datasets and R scripts used for the spatial analyses have been made available in an open-access repository (Rabuñal et al. 2022).

## Results

### Archaeostratigraphy

The archaeostratigraphic analysis revealed that no discrete archaeological sub-layers, separated by sterile sediments, can be documented across the excavation area. Figure 6 displays a selection of six archaeostratigraphic projections representative of the vertical distribution patterns of lithic remains across the excavated area. Three of them—column 7, column 9 and column 13—are oriented E-W, while



**Fig. 6** Spatial distribution and selected vertical archaeostratigraphic projections. Row E: N-S projection of the section  $x = 2.5-12$ ,  $y = 6.5-7$  (m). Row G: N-S projection of the section  $x = 2.5-12$ ,  $y = 4.5-5$  (m). Row K: N-S projection of the section  $x = 2-12$ ,  $y = 0-0.5$

(m). Column 7: E-W projection of the section  $x = 2.5-3$ ,  $y = 0-8$  (m). Column 9: E-W projection of the section  $x = 4-4.5$ ,  $y = 0-8$  (m). Column 13: E-W projection of the section  $x = 8.5-9$ ,  $y = 0-10$  (m). The striped area corresponds to the 2006 mechanical test trench

the other three—row E, row G and row K—follow a N-S orientation. These vertical projections allow to study the relationship between the vertical distribution patterns of the lithic remains, the topographic slope and the lateral stratigraphic discontinuities.

The vertical projections show a single archaeological horizon with a gentle SE slope, which presents a variable thickness throughout the excavation area related to the variable horizontal distribution of the lithic remains. It is thicker in the higher density areas, mainly to the S of the excavation area, and becomes progressively thinner towards the NW, with less and more dispersed lithic remains. The horizon thickness ranges from a minimum of 1 cm to a maximum of 30 cm, with a mean thickness of only 8 cm.

In some specific locations where the archaeological horizon is thicker, the vertical distribution of the lithic remains seems more dispersed (e.g. rows E–G in column 7, columns 7–10 in row G) than in others (e.g. columns 7–10 in row K, rows I–K in column 9). This vertical distribution pattern remains consistent with the effects of different low-intensity perturbation processes favoured by the penetrability of the sandy deposit such as trampling (Villa and Courtin 1983; Gifford-Gonzalez et al. 1985), pedoturbation (Rolfsen 1980; Vermeersch and Bubel 1997) or aeroturbation (Mayer 2002; Rick 2002). This is also in agreement with the soil formation, mesofauna activity and plant growth documented by micromorphology and

soil chemistry (Polo-Díaz et al. 2023; Fernández-López de Pablo et al. 2023).

## Lithic refitting

The study of lithic refitting allowed us to identify 38 groups of refits comprising a total of 86 remains, which results in a refit rate of 4.08% regarding the complete assemblage and of 8.35% excluding the microdebris. The refit types are distributed in 10 thermal conjoins (26.32%), 13 conjoins (34.21%) and 15 technical refits (39.47%) (Fig. 7, Supplementary Information SI2.1). Among the technical refits, one group includes both technical refit and thermal conjoin connections (REM\_7), and one includes both technical refit and conjoin connections (REM\_20). Except one refit group conjoining two fragments of a sandstone slab (REM\_12), all the refitted remains are on chert.

Most of the refit groups involve just 2 remains (33 out of 38; 86.84%), while 4 groups involve 3 remains and 1 group is composed of 8 remains. Altogether, 48 connection lines were identified: 18 thermal conjoin connections (37.5%), 9 dorso-ventral refit connections (18.75%), 3 flake-core refit connections (6.25%), 1 retouching connection (2.08%), 2 intentional fracturing connections (4.17%), 8 transversal conjoin connections (16.67%), 5 longitudinal conjoin connections (10.42%) and 2 Siret-fracture conjoin connections (4.17%).



**Fig. 7** Lithic refits from El Arenal de la Virgen: thermal conjoin (REM\_7, REM\_16, REM\_18, REM\_31), conjoin (REM\_14, REM\_15, REM\_36), flake-core refit (REM\_6), dorso-ventral refit (REM\_24, REM\_38, REM\_32), intentional fracturing refit (REM\_11)

**Table 3** Distribution of distance categories by type of refit connection

|                   | Refit | Conjoin | Thermal conjoin | Total |
|-------------------|-------|---------|-----------------|-------|
| Short (< 0.5 m)   | 5     | 5       | 10              | 20    |
| %                 | 33,33 | 33,33   | 55,56           | 41,67 |
| Medium (0.5–2 m)  | 8     | 5       | 7               | 20    |
| %                 | 53,33 | 33,33   | 38,89           | 41,67 |
| Long (2–4 m)      | 2     | 4       | 1               | 7     |
| %                 | 13,33 | 26,67   | 5,56            | 14,58 |
| Very long (> 4 m) |       | 1       |                 | 1     |
| %                 |       | 6,67    |                 | 2,08  |
| Total             | 15    | 15      | 18              | 48    |
| %                 | 31,25 | 31,25   | 37,50           |       |

Most connections are less than two meters long (40 out of 48; 83.33%), with a mean distance of 106 cm and a median distance of 59 cm. Thermal conjoin connections register the shorter distances, with a mean of 84 cm, most connections under 0.5 m, and one connection only is over 2 m long. Technical refits present a slightly longer mean distance—94 cm—with two connections over 2 m long. Conjoin connections document the longer distances, with a mean of 145 cm and five connections longer than 2 m (including the longer connection registered with 459 cm) (Table 3, Table 4, Fig. 8a, Supplementary Information SI2.2).

The bearings of connection lines larger than 0.5 m shown that there is not a preferential orientation of the refit connections (Fig. 8b, Supplementary Information SI2.2). The main plunge orientations are S and W, with 6 cases each, while 4 connections plunge towards the East and 3 towards the North and 2 are plain. The plunge angles are very low, with only 3 cases over 5° (Supplementary Information SI2.2). The mean angles of plunge are 3° for those plunged towards the North, 2.4° for those towards de East, 3.2° for those with a Southern slope and 4° for those plunged westwards. These values inform of the limited vertical displacement of the refitted artefacts, and are broadly consistent with the slope of the archaeological horizon.

**Table 4** Descriptive statistics of the connection distances by refit connection type

|                 | Refit | Conjoin | Thermal conjoin | Total |
|-----------------|-------|---------|-----------------|-------|
| <i>n</i>        | 15    | 15      | 18              | 48    |
| Min. dist. (cm) | 16    | 7       | 1               | 1     |
| Máx. dist. (cm) | 281   | 459     | 323             | 459   |
| Mean (cm)       | 94    | 145     | 84              | 106   |
| SD              | 81    | 142     | 87              | 107   |
| Median (cm)     | 62    | 66      | 47              | 59    |

These overall distance, orientation and plunge patterns are evidence of the good preservation of the assemblage's spatial pattern and the limited impact of cultural or natural post-depositional disturbance (Hofman 1981; Schiffer 1987; Morrow 1996; Petraglia 2002; Vaquero et al. 2007). The predominance of distances under 2 m for technical refits is consistent with the dispersal patterns described in experimental knapping works (Newcomer and Sieveking 1980; Barton and Bergman 1982; Schick 1986; Kvamme 1997; de la Torre et al. 2019). The fragments connected in thermal conjoins also show a highly clustered distribution with the shortest distance patterns (Fig. 8a, c; Table 3, Table 4). This finding is consistent with the distribution patterns described for the fragmentation of burnt lithics in experimental works (even the maximum distance connection is within the range of fragments and potlids expelled from the hearth) (Sergant et al. 2006; Frank and Baridón 2022). Conjoin connections show the highest representation of long and very long connections (> 2 m), including both Siret-fracture conjoins, which might be evidence of some intentional intra-site transport of certain lithic artifacts (Roebroeks and Hennekens 1990; Olive 2004; Kind 2013; Vaquero et al. 2017, 2019; Olive et al. 2019).

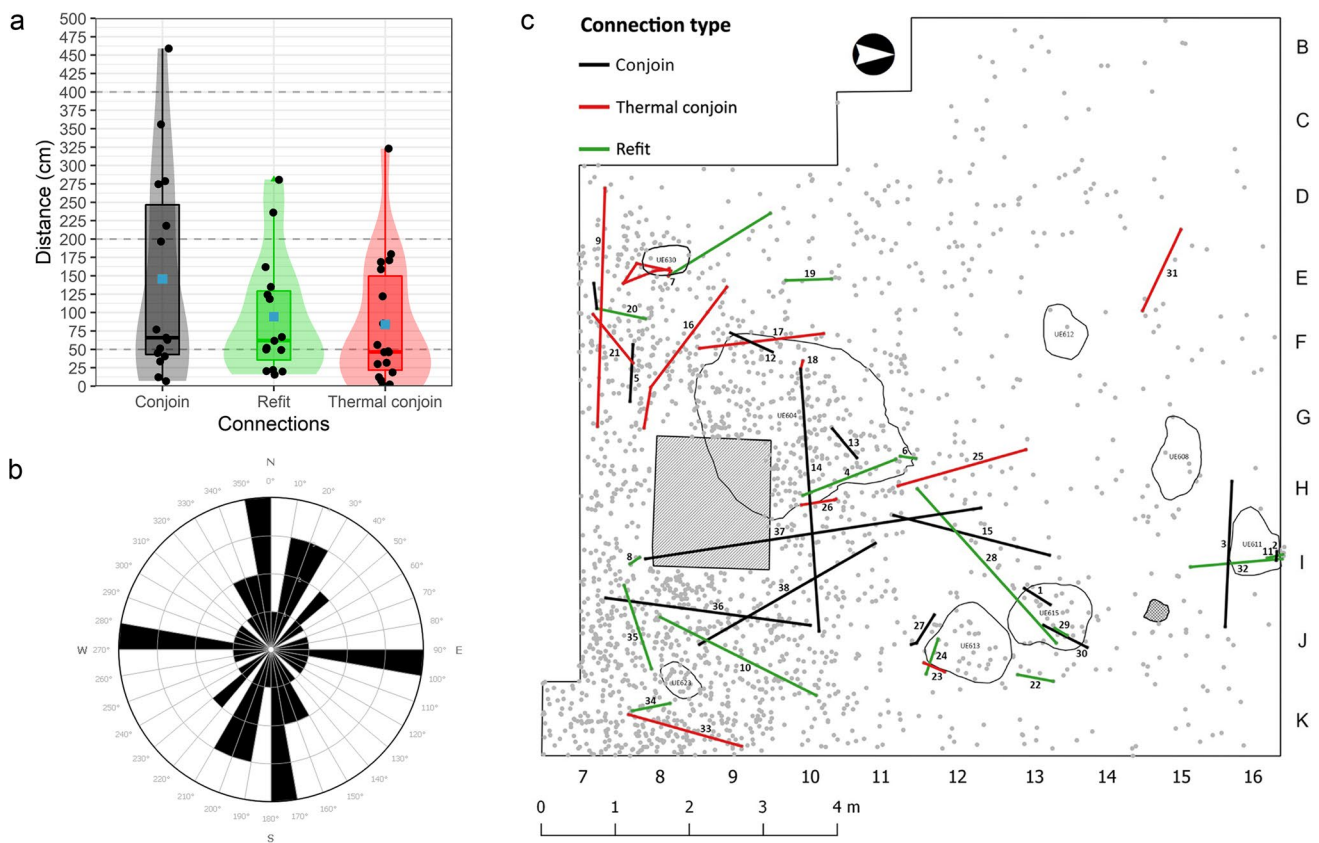
The spatial distribution of the lithic refits (Fig. 8c) shows that hearth-related activity areas are well preserved, given that the connections are concentrated within and around the combustion structures and occupation features. Refits related to the structures dated to Phase 1 are highly clustered around one of the structures (SU 611) and comprise short and medium distance technical and conjoin connections, some between large elements (REM\_11, REM\_32). Conversely, refit groups related to the structures dated to Phase 2 are more numerous and more diverse, with 13 technical refits, 11 conjoins and 10 thermal conjoins. In addition, Phase 2 refits show a broader spatial distribution pattern and a higher connection distance variability, although short and medium connection distances remain dominant.

### Spatial analysis

The mean density per m<sup>2</sup> or point intensity ( $\lambda$ ) is 24.82 points/m<sup>2</sup>. However, the lithic remains associated with Unit IV show uneven spatial distribution across the excavation area, with a clear difference between the S and the N sectors regarding the overall presence of remains. This appreciation is quantitatively corroborated by the Hopkins-Skellam test, which indicates a clustered distribution pattern of the lithic assemblage ( $A = 0.22289$ ;  $p = < 2.2e-16$ ).

The visualisation of the distribution pattern of the complete lithic assemblage, through the point pattern projection (Supplementary Information SI2.3) and the kernel density map (Fig. 9a), shows how the previously characterised





**Fig. 8** Box plot, jitter plot and violin plot with the connection distances (cm) of the different connection types considered (conjoin, refit and thermal conjoin). Blue square represents the mean distance for the corresponding connection type. Dashed lines indicate the threshold for the considered distance categories (short: < 50 cm;

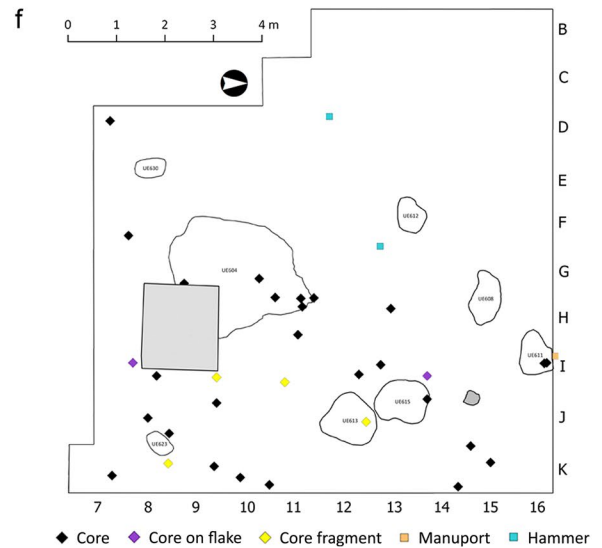
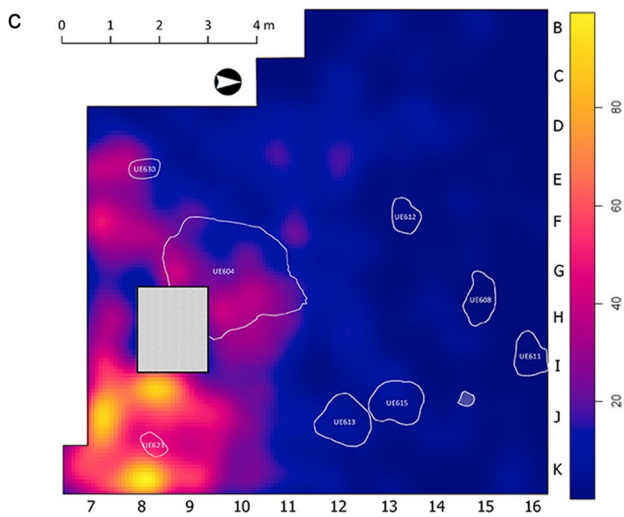
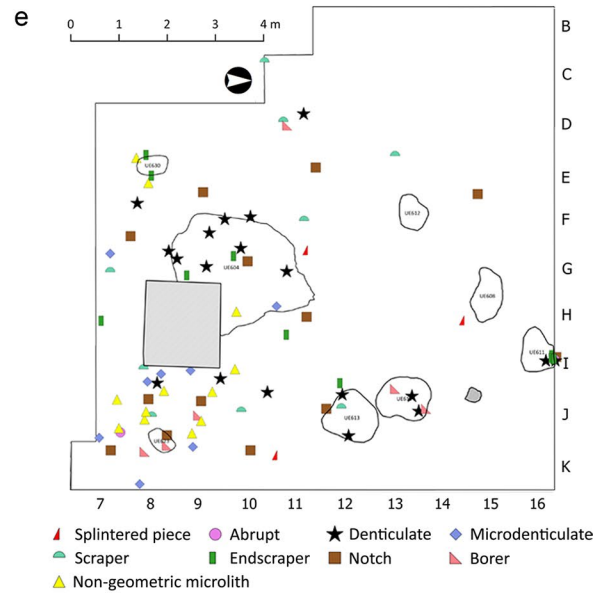
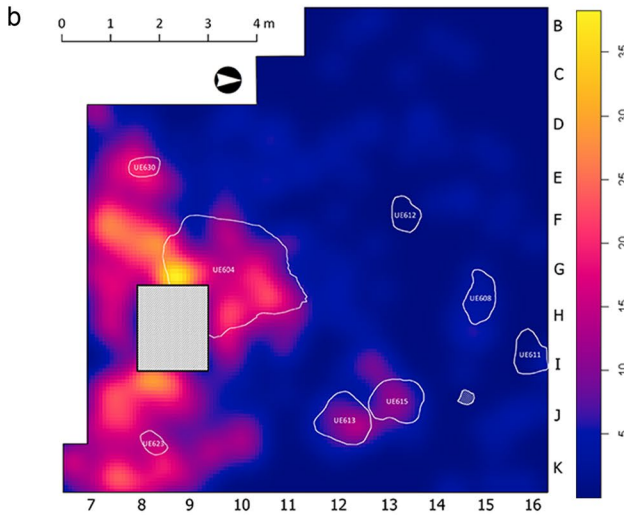
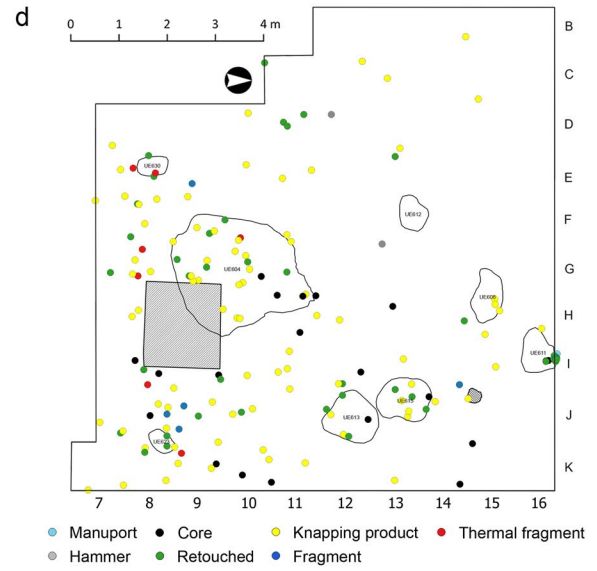
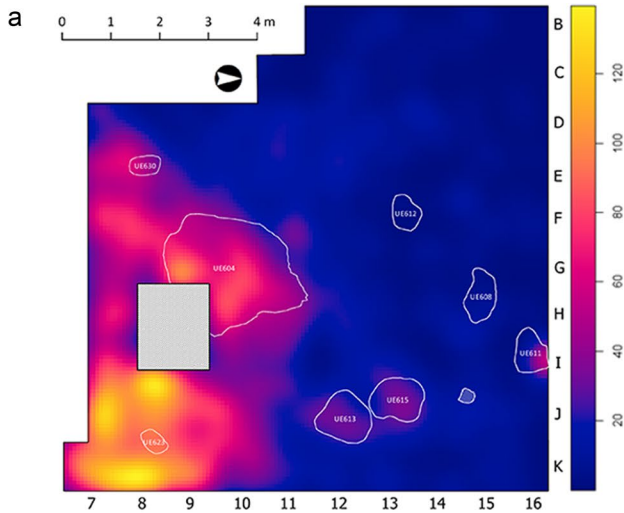
medium: 50–200 cm; long: 200–400 cm; very long: > 400 cm) (a). Rose diagram representing the orientation patterns of refit connections longer than 0.5 m (b). Spatial distribution of the lithic refit connections from El Arenal de la Virgen (black: conjoin; red: thermal conjoin; green: refit) (c)

clustered distribution model is expressed in the spatial variation of the remains density. Varying sizes of high-density concentrations are distributed across the excavation area and separated by low-density dispersions. Although some isolated minor concentrations are visible, for example in squares F 7-8 or H 7-8, higher density areas are mainly spatially associated with the different occupation features, with the highest density accumulation located in squares I-K 7-10 associated to SU 623. This observation was quantitatively corroborated through the Cross-type L-function (Fig. 10), which confirms the spatial dependence of the lithic remains distribution regarding the distribution of the features.

Burnt lithics show a similar distribution pattern to the complete assemblage (Fig 9b, Supplementary Information SI2.3). Again, the densest areas of burnt remains tend to coincide with the structures, although now the area with the highest density is related to SU 604. In some cases, they are mainly concentrated within the structure perimeter, as in the case of SU 613, 615 or 630. However, some other areas present broader distributions, even reflecting different concentrations or peaks in density within an occupation feature—as

in the case of SU 604 (squares G9, H10, G11)—or in the surroundings of a combustion feature—as in the case of SU 623 (square I9) and SU 630 (squares F 7-8). These independent areas of accumulation of burnt remains could represent evidence of different burning events or dump locations from the cleaning of hearths.

Microdebris show a marked clustered distribution with considerable differences in density of remains across the excavation area (Fig. 9c, Supplementary Information SI2.3). As for the complete assemblage, the main microdebris concentration is located in the SE area, with three peaks surrounding SU 623. A differential distribution of microdebris is noticeable in SU 604, with two separate concentrations in squares G-H 10-11 and G9. To the SW, as well as for the complete assemblage and the burnt remains, one concentration directly associated with SU 630 is documented as well as a separate one in squares F 7-8. A scarce presence of microdebris is documented for the rest of the occupation features (SU 608, 611, 612, 613 and 615). Even though microdebris are present in these latter areas in the point pattern projections (Supplementary Information SI2.3), they are not



**Fig. 9** Spatial distribution of the lithic remains from El Arenal de la Virgen: kernel density map of the complete lithic assemblage (a); kernel density map of the burnt lithic remains (b); kernel density map of the microdebris (c); categorised point pattern projection of the large lithic remains by structural category (d); categorised point pattern projection of the retouched artefacts by typological group (e); categorised point pattern projection of the knapping elements by structural category (f)

so clearly visible on the Kernel Density maps (Fig. 9c) given the large differences in absolute frequency of lithic remains in comparison to the densest areas of the site.

Broadly, the spatial distribution of large remains (Fig. 9d), retouched artifacts (Fig. 9e), and knapping elements (Fig. 9f) supports the strong spatial relationship between discard patterns and occupation features. However, they also show some specificities that are relevant for the interpretation of the palimpsest and site structure characterisation that will be discussed further below.

The spatial proximity of the different occupation features prevents the identification of distinct toss zones away from the features. However, one can clearly observe the concentration of large elements, retouched artifacts, and knapping elements within or immediately adjacent to the perimeter of all the features (except for SU 612). This suggests a discard pattern related to either large elements remaining in the drop zones or their tossing towards the hearths.

The spatial distribution of knapping elements and retouched artifacts reflect a number of noticeable differences both in their overall spatial patterning and their specific location within the hearth-related areas. On the one hand, the different concentrations in the western area (SU 630 and secondary concentrations in squares F-G 7-8 and D-E 10-12) document abundant retouched artifacts but few cores, while in the rest of the excavated area, their presence is more or less concurrent. On the other hand, the internal distribution pattern of most hearth-related areas is qualitatively “nondifferentiable” (evident for SU 611 and apparent for SU 613, 615 and 623). However, in the case of SU 604, the cores are concentrated towards the northern section of the feature—adjacent to the vertical block in SU 625—and retouched artifacts become more abundant—especially denticulates—towards the southern section of the feature.

The spatial distribution of the complete lithic assemblage, specific artifacts categories, large remains, burnt remains, and microdebris, display a consistent relationship with the preserved occupation features, forming discrete patches. Yet, they also show the presence of a number of secondary concentrations, which are not directly related to those features.

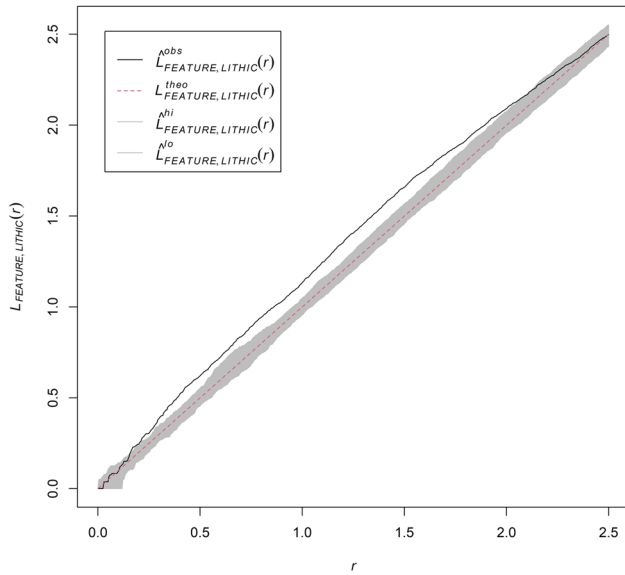
However, when analysing the spatial distribution of some phenomena regarding the formation processes and site structure, we must question the extent to which some of those patterns visible on the kernel density maps, may be a by-product of the overall lithic distribution. For example, in the

case of the burnt lithics one could expect that, in absolute terms, areas with more lithic remains would also present more burnt remains with respect to other areas with lower lithic remains density. And this would thus show on the kernel density map. Therefore, the KDE may reflect the spatial variation of the absolute frequency of burnt lithic remains, mirroring in some way the spatial variation of the lithic assemblage, but not the spatial variation of the relative thermal impact on the lithic remains across the occupation area.

The burnt microdebris index allows to approach this question in relative terms (Fig. 11). Overall, the burnt microdebris index shows a rather low but variable fire alteration of the microremains (mean = 0.27; SD = 0.24; IQR = 0.12–0.33). These values should be interpreted with caution, however, considering the high variance of this index, due to the modest sample size in some areas. The visualisation of the variation of the burnt microdebris index across the excavation area (Fig. 11a) provides evidence of non-uniform relative thermal damage of the deposited materials, ranging from areas where approximately 40–50% of the microdebris are thermally altered (e.g., squares G9 or J13-14), to others with less than 10% of burnt microdebris. The spatial autocorrelation analysis of the burnt microdebris index (Fig. 11b) shows the presence of several discrete areas with a statistically significant concentration of high values (red points in Fig. 11b, labelled as high clusters), while statistically significant clusters of low values (blue points in Fig. 11b, labelled as low clusters) are less common.

Some high clusters are directly related to combustion features (in square E8 to SU 630 or in squares I-J 13-14 to SU 615), while other combustion features document a low or statistically non-significant relative thermal impact on the associated materials (such as SU 613 and 623 with abundant assemblages, or SU 608, 611 and 612 with scarce associated assemblages that make the weighing difficult). Moreover, three other high clusters present great interest. The cluster in squares F7-8 is independent with regard to the closest combustion feature (SU 630) and coincides with an isolated concentration documented in the spatial distribution of all the other artifact categories previously analysed. The other two are located within SU 604 but as independent and discrete high clusters, one towards the S section of the feature (around square G9) and the other towards the N section (in squares G-H 11 adjacent to the vertical block in SU 625). This reinforces the dual distribution pattern also detected in other artifact categories such as retouched artifacts and cores or microdebris.

In sum, this quantitative analysis reveals the presence of different discrete combustion loci affecting the lithic scatters, some of which are not coincident with the preserved structures, while some others unveil multiple combustion focuses within the perimeter of a presumed single structure prior to our analysis. The relationship between the spatial



**Fig. 10** Cross-type L-function contrasting the spatial dependence between lithic remains and occupational features (red dashed line: theoretical CSR function; gray area: acceptance region for random point type assignment; black line: empirical function; r: distance (m))

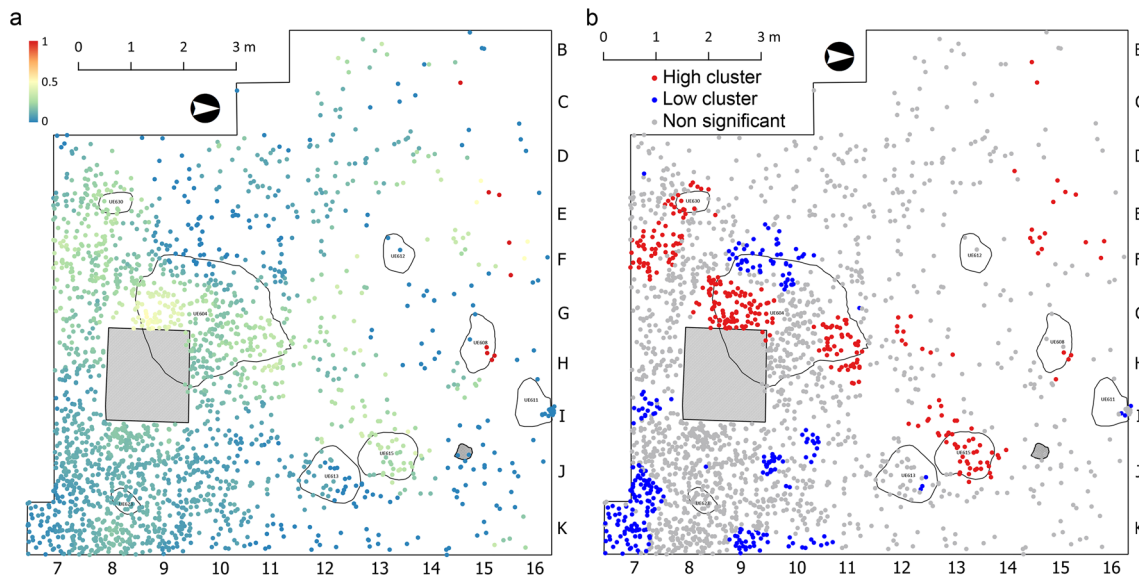
location of these combustion loci and the spatial distribution of the different lithic artifact categories analysed suggests the presence of diverse hearth-related accumulations, likely associated to activity areas. The latter in turn informs us of the formation of a palimpsest indicating a recurrent use of the space and superimposed activity areas.

## Discussion

### Characterising the El Arenal de la Virgen Early Mesolithic palimpsest

From an archaeostratigraphic perspective, the Unit IV of El Arenal de la Virgen has been characterised as a rather homogeneous and thin archaeological horizon. The stratigraphic and sedimentary analyses documented the presence of different post-depositional processes such as soil formation, deflation or surface processes (Polo-Díaz et al. 2023; Fernández-López de Pablo et al. 2023). We cannot rule out the possibility that these processes led to the fusion of different archaeostratigraphic sub-layers on different sectors of the site. However, the absence of size sorting, together with the spatial distribution of lithics and refittings, and the refit distance and orientation patterns, rule out the presence of reworking by high energy processes supporting, instead, the integrity of the lithic assemblage and the good preservation of the spatial pattern.

Nevertheless, even in relatively well-preserved/high-resolution contexts like Unit IV of El Arenal de la Virgen, it is most likely that by preconceiving a single occupation floor one will be adopting a Pompeii premise (Ascher 1961; Schiffer 1976, 1985; Binford 1981) and will thus overlook the archaeological reality (Dibble et al. 1997). Here, a straightforward correlation with ethnoarchaeological models of site structure would entail an interpretation of the



**Fig. 11** Spatial variation of the burnt microdebris index (each point's colour represents the relative frequency of burnt microdebris in a 1 m<sup>2</sup> neighborhood in a continuous colour ramp from 0% in blue to

100% in red with 50% in yellow) (a); spatial autocorrelation analysis of the burnt microdebris index (red: high clusters; blue: low clusters; gray: non-significant; statistical significance at 95%) (b)



excavated area as a household activity area in a residential camp, with a dwelling space and multiple hearth-related domestic activity areas corresponding to a single occupation phase (Yellen 1977; O'Connell 1987; Fisher and Strickland 1989).

However, the integrated and quantitative analysis conducted here reveals a more complex archaeological scenario; one that is indispensable to advance a more solid and reasoned characterisation of site occupations.

### Disentangling the palimpsest: occupation phases, features and spatial distribution.

The systematic radiocarbon dating of the occupation features and the chronological modelling provided unequivocal evidence of the presence of two distinct and short-lasting chronological occupation phases, separated by a chronological hiatus (Fernández-López de Pablo et al. 2023).

The first Mesolithic occupation phase is represented by SU 608, interpreted as a possible oven, and SU 611, interpreted as a dumping feature of combustion residues possibly originated in the earlier structure (Polo-Díaz et al. 2023). Both structures are spatially associated with an area of very low density of lithic remains (squares F-J 15-16). Lithic refits are also scarce, with two conjoins and two technical refits that are highly clustered around SU 611. This distribution pattern is consistent with hearth-related assemblages showing minimal activity intensity (Vaquero and Pastó 2001). However, given the above mentioned characterization proposed for these features, other plausible cause could be the clearing of the activity area (Stevenson 1985; Wandsnider 1996). Unfortunately, the evidence associated with this first occupation phase is limited to the N boundary of the excavation area, which restricts the perspective we could obtain for its characterisation. The partial affection by erosive processes cannot be completely dismissed in this particular area (Fernández-López de Pablo et al. 2023).

The second occupation phase comprises most of the uncovered archaeological evidence according to the radiocarbon dating of the rest of the features. There is a total of six archaeological features associated with this phase: two hearth-pits (SU 613 and 615), one surface hearth (SU 623), one shallow pit (SU 612), one posthole with a supporting wedge (SU 625) and a disturbed dwelling area (SU 604). The remaining surface hearth SU 630 is not directly dated.

This phase, covering most of the excavated area, offers a more extensive context for approaching site formation processes, site structure and the nature of the occupation. Correspondingly, the lithic assemblage associated with this phase is larger and the lithic refits are more numerous and variable in type, connection length and distribution, including multiple technical refits—with core-flake, dorso-ventral

and retouching connections—though all are short sequence connections.

Lithics show a close spatial relationship with the occupation features, forming different accumulations with variable remains densities, and thus indicating a spatial structuring of the space characterised by rather well-preserved activity areas. In some cases, the proximity of features makes it difficult to recognise the discrete accumulations due to their partial superposition. Overall, however, the spatial distribution pattern of the lithic remains is consistent with a model of hearth-related assemblages (Vaquero and Pastó 2001). On the other hand, according to the distribution and alteration patterns on the burnt lithic remains, the tossing of large elements towards the hearths, probably while the fire was still active (Sergant et al. 2006; Alperson-Afil 2012; Frank and Baridón 2022), is well documented.

Still, we could delve further into the palimpsest structure and formation and disentangle multiple indicators of space use recurrence and superposition of activity events, which are not necessarily contemporaneous, helping us to better understand the occupation of the site. Among the most explicit indicators of the nature of this palimpsest is the distribution of the combustion loci detected through the analysis of the Burnt Microdebris Index.

These different combustion loci, and especially those outside the hearth-pit structures, can have different nature. They could be related to the dispersion/discarding of residues from the cleaning and maintenance of combustion features (Stevenson 1985; Wandsnider 1996). However, no evident traces of maintenance practices or secondary deposition areas (dumps) have been identified neither in the sedimentary fill of the Phase 2 features (Polo-Díaz et al. 2023) nor in the spatial patterns of the lithic remains. In light of the spatial patterns described before, we argue that more probably they would correspond to latent or phantom hearths, non-preserved or less structured combustion areas or the remaining traces of dismantled combustion features affected by the superposition of activities over time (Leroi-Gourhan and Brézillon 1972; Petraglia 2002; Sergant et al. 2006; Alperson-Afil et al. 2009; Alperson-Afil 2012, 2017; Aldeias et al. 2016; Aldeias 2017; Sánchez-Romero et al. 2020). This adds another potential dimension to the palimpsest character of Unit IV, since they may be related to combustion events from either Phase 1, Phase 2, or even another occupation phase not documented in the available radiocarbon record.

The distribution of the different combustion features and loci, complemented by the spatial distribution of the studied artifact categories and refits, help to capture spatial patterns consistent with veiled hearth-related activity areas. The concurrence of other traces, such as the density of remains, the thickness of the archaeological horizon, the tighter or more diffuse distribution of the lithic remains and refit connections regarding the feature, or the definition or

blurring of the spatial patterns, allow us to further detail the formation processes of the accumulations (Stevenson 1985, 1991; Brooks and Yellen 1987; Vaquero and Pastó 2001; Clark 2017).

On one hand, SU 613 and SU 615 (squares I-K 12-14), despite being adjoining, preserve well-defined concentrations of artifacts and clustered short distance refit connections, distributed in a thin layer, which may be indicative of low-intensity activity and low disturbance by posterior activity events. The statistically significant higher burnt microdebris index in SU 615 might suggest a later use, affecting materials already deposited in a drop zone related to SU 613.

On the other hand, the accumulation related to SU 623 (squares I-K 7-10) shows a higher density of remains and a broader vertical distribution, as well as a more diffuse horizontal distribution of the lithic remains—illustrated by the different artefact categories as well as by the fire alteration—blurring the expected primary distribution patterns of a hearth-related activity area that are observable in other areas of the site. Refits distribution and connection distances are also wider, although refit sequences remain short. These traces, together with the less structured preservation state of the feature, are indicative of a cumulative palimpsest product of a more intense use of the space, which may include intentional clearing of the activity area and/or unintentional trampling and scuffage (Stevenson 1985, 1991).

The case of SU 604 is also noteworthy, despite the inconvenience of a lack of data in the mechanical test pit area. Within the perimeter documented in the field for SU 604 (squares F-H 9-11), two different combustion loci were unveiled (squares G-H 11 and G9) which correlate with different drop zones (differential microdebris distribution peaking in G-H 10-11 and G9) and a dichotomous distribution of cores and retouched artifacts. In addition, technical refits and conjoins are concentrated in the locus with cores (G-H 10-11). This complex pattern does not necessarily dismiss the possibility of the presence, in this area, of a dwelling or shelter structure—still supported by its size and shape and its association with a vertical block possibly placed as a post wedge (Grøn 2003; Verjux et al. 2003)—where spatially segregated activities would have taken place. Yet, it could also signal a possible recurrence of space occupation and use by distinct activity events—possibly not all of them related to a dwelling space—that might also explain the increased thickness of the archaeological horizon in this sector. This is also supported by microstratigraphic evidence of palimpsest formation of SU 604 (Polo-Díaz et al. 2023).

Finally, on the SW section (squares D-F 7-8), the different analyses allowed to decipher a spatial pattern compatible with two hearth-related activity areas, one associated with the surface hearth SU 630 and the other with the concealed combustion loci in squares F 7-8. Both the presence of a latent combustion loci and the less structured preservation

of SU 630 may suggest a more intense affection on this area by recurrent use of space. SU 630 remains undated, adding more uncertainty to the interpretation of this areas and their correlation with the occupation history of the site. However, the consistency of the radiocarbon record on the spatial segregation of Phase 1 and Phase 2 features suggests that these features and associated activity areas would be related to recurrent use during Phase 2.

### Unraveling occupation patterns

The previous discussion illustrates that the Unit IV of El Arenal de la Virgen represents a dynamic surface, result of a complex accumulation of different superimposed events that are not distinctive nor easily identifiable (Brooks and Yellen 1987; Vaquero and Pastó 2001). The temporal dimension of the use of these spaces is particularly difficult to elucidate, whether through a higher intensity/length activity of some areas or multiple different activity events overlapping in the area.

Bidirectional refit connections between different accumulations are considered a solid proxy for supporting an interrelationship between activity areas, indicative of contemporaneity (Hofman 1981; Villa 1982; Czesla 1990; Vaquero 2008; Romagnoli and Vaquero 2019), but none has been documented. Instead, refits are clustered within each accumulation showing predominantly short distance connections. In addition, short and partial refit sequences, with the presence of ghosts and orphans in the refitting sets, are indicative of short occupations by highly mobile groups (Morrow 1996).

The information available and all the data discussed above suggests that a spatial and cumulative palimpsest formed in Unit IV, but with a limited loss of spatial resolution. That is, a palimpsest where neither the natural post-depositional processes, nor the accumulation of different anthropic occupation and activity events have had a major impact on the preserved structures and the integrity of the activity areas. We argue that the Mesolithic archaeological evidence documented in El Arenal de la Virgen is not related to a single prolonged occupation in a residential camp within a settlement pattern characterised by low residential mobility, neither to a large camp representing the aggregation of multiple bands. Not even during the second chronological occupation phase where evidence of habitat structures is larger.

The low density of lithic remains and the good preservation of the spatial patterns, even when there is solid evidence of multiple overlapping activity events within the same spaces related to recurrent use, suggests a low occupation intensity that would point to short-term temporally distinct activity events (Yellen 1977; Binford 1978a; Stevenson 1985, 1991; Brooks and Yellen 1987; O'Connell 1987;

Tani 1995; Cascalheira and Picin 2020). Thus, we infer that the Mesolithic settlement pattern in El Arenal de la Virgen is more likely related to the concurrence of different and recurrent short-term occupations by highly mobile groups, probably of a seasonal nature, and even possibly presenting variable site functions.

We must, nevertheless, remain cautious, given that we do not know the complete surface area of each occupation phase. This is especially true beyond the excavation limits but also regarding any possible mixing between them that we may not have been able to detect within the palimpsest.

### Early Holocene open-air palimpsest research in the Iberian Peninsula: a limited framework for contextualizing El Arenal de la Virgen

Over the past years, there have been discovered, excavated—mainly through rescue programs—and published various Early Holocene open-air sites. They provide evidence of occupations spanning several chrono-cultural periods or within broad chronological limits. Unfortunately, the disparate and rather limited research efforts devoted to most of the known open-air sites prevents us from discussing in extension the results obtained in this work with comparable data. This lack of studies also impedes us the building of in-depth knowledge of each site's occupation histories and thus the characterisation of open-air settlement patterns.

The only cases for which works have been reported that jointly consider archaeostratigraphic, lithic refitting and intra-site spatial distribution approaches are Font del Ros (Martinez-Moreno and Mora 2011; Roda Gilabert et al. 2013, 2016) and Barca do Xerez Baixo (Araújo and Almeida 2007, 2008, 2013). Although each case presents its own specificities, both studies suggest a problematic that is analogous to that documented for El Arenal de la Virgen. Each site shows multiple post-glacial occupation phases based on the identification of different archaeostratigraphic layers (two in Font del Ros and three in Barca do Xerez Baixo). In addition, a limited yet informative record of radiocarbon dates also indicates a dilated chronological framework regarding their respective occupation spans. In both sites, refitting studies reached similar refit rates to that of El Arenal de la Virgen: approximately 5–7%. The spatial distribution of refits and archaeological materials (lithics, faunal and plant remains) are evidence of the good preservation of different hearth-related activity areas.

Unfortunately, Barca do Xerez Baixo was excavated in different sectors and the excavation surface areas were relatively small (the largest covers 35 m<sup>2</sup>). This prevents an evaluation of the spatial organisation of the different occupation phases. On the other hand, an extensive open area of over 1200 m<sup>2</sup> was excavated in Font del Ros, thus constituting

a highly valuable reference for the spatial organisation observed in El Arenal de la Virgen.

Throughout the extensive excavated area of Font del Ros, the spatial distribution of archaeological evidence defines two main occupied areas (SW sector with c. 100 m<sup>2</sup> and NE sector with c. 350 m<sup>2</sup>) spatially differentiated by an area with little evidence. Each of these main zones is composed by different discrete concentrations of archaeological materials in spatial association with combustion features, determining well-preserved activity areas. Refits show a predominance of short distance connections, mainly circumscribed to specific hearth-related activity areas and showing minimal interaction between different activity areas within and between the main zones. In light of these results, the occupation of the main Mesolithic level of Font del Ros has been interpreted as corresponding to an indeterminate number of events where, as also suggested by the radiocarbon dates, the two main occupied zones functioned independently (Martinez-Moreno and Mora 2011; Roda Gilabert et al. 2016).

Interestingly, it has also been suggested that some of the other less-studied postglacial open-air sites correspond to multiple non-contemporaneous occupations, based on a range of evidence: the presence of a palimpsest of numerous occupation features and the abundance of lithic remains in Benàmer (Torregrosa et al. 2011); the diversity of structures—domestic features and burials—and their chronological dimension in Casa Corona (Fernández-López de Pablo et al. 2013, 2014, 2015) and El Collado (Gibaja et al. 2015; Fernández-López de Pablo 2016); the documentation of low densities of materials and features across dilated chronological spans in the two Mesolithic layers of Prazo (Monteiro-Rodrigues 2011); or the site surface area and the good definition of the different activity areas in Vale Marim I (Soares and Tavares da Silva 2018). However, these interpretative hypotheses are based more on qualitative inferences from different site traits, which alone may suffer from equifinality such as the density of features or site area (Hamilton et al. 2018); or on specific studies on single proxies, such as the chronological frameworks, which represent a solid basis for detecting occupation spans but are not informative regarding the nature of the occupations if not integrated with other studies.

Conversely, it has been suggested that sites such as Sota Palou (CRPES 1985), Cabezo de la Cruz (Rodanés and Picazo 2013) and Parque Darwin (Escobar 2010) would represent a single short-term seasonal occupation associated with the documentation of a hut floor. Nevertheless, the reduced size of the excavated surfaces (40 m<sup>2</sup>, 12 m<sup>2</sup> and 77 m<sup>2</sup>, respectively) and the limited spatial and chronological information available call for cautious interpretation, at least for now.

The proper characterisation of the open-air occupation dynamics has major implications regarding the

understanding of the economic and social drivers of postglacial settlement systems. Besides, the fundamental components of ethnohistoric hunter-gatherer camps (household units, hearths, activity areas, etc.) and their occupation characteristics (duration, number of occupants, camp area, etc.) present a number of consistent relationships that help to interpret the spatial structure and scale of archaeological hunter-gatherer camps (Binford 1977, 1978a; Yellen 1977; Binford 1978b, 1980; Gould 1978; Kent 1987; O'Connell 1987; Brooks and Yellen 1987; Fisher and Strickland 1989; O'Connell et al. 1991; David and Kramer 2001; Kelly 2013; Hamilton et al. 2018).

In the Iberian Peninsula, these open-air sites have generally been interpreted as central or residential camps, with the exception of Barca do Xerez Baixo which has been interpreted as a hunting camp (Araújo and Almeida 2013). They are all located close to water sources and on ecotones, allowing access to various local ecosystems and resources. These sites are therefore expected to play a notable role in the settlement systems, sustaining perhaps prolonged occupations or constituting referential aggregation places, as well as frequent reoccupations (Schlanger 1992; Smith and McNees 1999). Moreover, it has been argued that many were of a seasonal nature, linked to the consumption of seasonal low-range resources such as hazelnuts (CRPES 1985; Martínez-Moreno and Mora 2011; Roda Gilabert et al. 2013, 2016), acorns (Berihuete Azorín et al. 2017) or edible land snails (Fernández-López de Pablo et al. 2011b).

Based on the discussion above, it seems that in these postglacial open-air sites, the formation of palimpsests linked to recurrent short-term reoccupations by small and highly mobile groups might be common, rather than a predominance of long-term occupations or large aggregation camps. However, regarding the function of these short-term occupations—whether residential or task specific—there seems to be differences among the sites, and possibly even within each particular site's occupation sequence.

Multiple traits guide the characterisation of site functions and deserve to be further studied, contextualised and comparatively discussed. Such traits include, for example: the presence/absence of dwelling features; the density of lithic remains and other refuse (e.g., the presence/absence of dump deposits or shellmiddens); the variability in the composition of the tool assemblages (e.g., the presence/absence of grinding stones for plant processing); the subsistence activities developed; or the density of features and remains regarding chronological spans. Yet, in addition to the above, one of the most remarkable differences is the presence of burials. In most known open-air sites, irrespective of the excavated surface areas, occupation evidence is mainly composed of hearth-related activity areas scattered throughout the occupied space. In some sites, however, cemeteries with an extensive inhumation record are documented,

added to other occupation evidence, such as in El Collado (Fernández-López de Pablo 2016; Terradas et al. 2016) or the shellmiden sites in the Muge and Sado estuaries (Carvalho 2009; Bicho et al. 2010, 2013; Peyroteo-Stjerna 2020), or sporadic burial practices e.g., in Casa Corona (Fernández-López de Pablo et al. 2013).

Such a scenario supports the need to promote the application of extensive, quantitative, multidisciplinary and integrated approaches to the analysis of palimpsests. They have indeed proven to be exceptionally informative in the case of El Arenal de la Virgen, as well as in other contexts and case studies that have adopted different multidisciplinary research strategies (Crombé 2005; Zubrow et al. 2010; Carbonell 2012; Julien and Karlin 2014; Séara 2014; Mallol et al. 2019; Marín et al. 2019; Spagnolo et al. 2020b; Real et al. 2020; Sánchez-Romero et al. 2020; Spagnolo et al. 2020a; Moncel et al. 2021; Vandendriessche et al. 2022). Extending this kind of research to different kinds of contexts would improve our knowledge of intra-site occupation dynamics and regional settlement systems. Specifically, regarding the postglacial open-air settlements in Iberia, some sites that are already known but that have not yet been extensively studied hold much potential and sufficient information available to be further explored. It would be possible to delve deeper into the chronological dimension of the occupations, the reconstruction of palimpsest formation processes and the characterisation of site structures and occupation histories.

## Conclusions

The present case study illustrates the complexities of defining site occupation histories and deriving interpretations of site structure and occupation models, stressing the importance and huge potential of addressing the palimpsest as an analytical unit as well as of assessing spatio-temporal assemblage integrity and site formation processes through integrated multidisciplinary approaches. This way, it is possible to disentangle occupation segments and gain more in-depth knowledge of the site structure across the site's occupation history. Such a step plays a key role in addressing the palaeoethnographic dimension of archaeological occupations. Ethnoarchaeological models are a key reference for archaeological interpretations, but we cannot sustain interpretations of archaeological site structures based on Pompeii-like premises. We must always bear in mind the temporal dislocation between the ethnoarchaeological time and the archaeological time, and address it strategically to the greatest extent possible.

The postglacial archaeological record is an optimal scenario for developing this kind of research, offering preservation conditions and potential resolution capability, especially regarding the possibility of obtaining detailed chronological



frameworks. And such capabilities are well-suited to the integration of multiple high-resolution proxies.

In the case of El Arenal de la Virgen, we developed a high-resolution multidisciplinary approach which integrated: chronological modelling, using an extensive dating program (Fernández-López de Pablo et al. 2023); geomorphological and micromorphological information (Polo-Díaz et al. 2023); the archaeostratigraphic study of the archaeological horizon; the behavioural and taphonomic information provided by lithic refitting; and a comprehensive intra-site spatial distribution analysis exploiting the flexibility of novel quantitative methods to target specific questions regarding palimpsest formation and site structure.

This exhaustive study allowed the identification of a spatial and cumulative palimpsest, even in a relatively small excavation area by open-air site surface area standards. This palimpsest was associated with two chronological occupation phases and formed by the accumulation of well-preserved but seemingly asynchronous activity events.

This characterisation provided an invaluable perspective on the definition of site occupation patterns. It allowed to dismiss the interpretation of the excavated Mesolithic evidence of El Arenal de la Virgen as part of a large, long-term occupation camp or an aggregational locale. On the contrary, the study suggests a settlement pattern related to recurrent, short-term episodes of site reoccupations by highly mobile small groups.

The results obtained here underscore the need to promote integrated research programs specifically designed to address open-air contexts. These programs would include the development of intervention protocols laying the basis for multidisciplinary approaches (high-resolution spatial recording methods, thorough material curation, systematic sampling for chronological and sedimentological studies, etc.). They should also encourage additional studies on known open-air sites in order to build a deeper knowledge of their occupation histories.

The possible extrapolation of this interpretation to other known open-air sites in the Iberian Peninsula reinforces their preeminent role in postglacial settlement systems. The site functions, however, would be variable, linked to recurring seasonal returns to specific and highly valuable localities, possibly for a range of purposes which require and deserve further investigation.

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**Code availability** The datasets and code scripts used for the intra-site spatial analysis are available in Zenodo: <https://doi.org/10.5281/zenodo.6656479>.

## Declarations

**Competing interests** The authors declare no competing interests.

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