



From stone to tool: how raw materials influenced Upper Palaeolithic technology in southwestern Iberia (Vale Boi)

Joana Belmiro¹ · Nuno Bicho¹ · Xavier Terradas² · João Cascalheira¹

Received: 15 April 2025 / Accepted: 7 October 2025 / Published online: 10 November 2025
© The Author(s) 2025

Abstract

The Upper Palaeolithic (UP) of westernmost Europe was marked by technological and cultural transformations and abrupt climatic shifts. The Iberian Peninsula, particularly southwestern Iberia, served as a refugia and key eco-cultural niche, making it a key region for UP studies. Vale Boi, the only site in southwestern Iberia with a nearly complete UP sequence, provides critical insights into technological, economical and mobility patterns over time. This study examines lithic raw material procurement and technological organisation at Vale Boi, focusing on the differences between local and non-local cherts. We analysed chert assemblages from Gravettian, Proto-Solutrean, and Solutrean levels, integrating previously published techno-typological and raw material macroscopic and petrographic data. Our results indicate that non-local cherts were intensively reduced. The presence of varied techno-typological classes suggests that non-local cherts were not exclusively transported as finished tools, instead highlighting their role as versatile, transportable raw material volumes. Gravettian occupations exhibited greater reliance on non-local cherts, suggesting short-term occupations and higher mobility, while Proto-Solutrean and Solutrean occupations showed increased dependence on local materials, suggesting long-term occupations. These findings expand our understanding of UP technological adaptations in southwestern Iberia, emphasising the complex role of lithic resources in mobility, settlement, and social networks.

Keywords Upper palaeolithic · Lithic technology · Hunter-gatherer mobility · Chert procurement · Iberian peninsula

Introduction

The Upper Palaeolithic (UP) in Europe, dating to approximately 40,000–10,000 years ago, was marked by significant technological innovations, shifts in subsistence strategies, and the emergence of diverse regional traditions (Straus 1995; Gamble et al. 2004).

In westernmost Europe, five main technocomplexes have been identified within the UP—Aurignacian, Gravettian, Proto-Solutrean, Solutrean, and Magdalenian—each contributing new evidence on resilient behaviours and cultural continuity. These technocomplexes are distinguished by regional adaptations as well as technological and

subsistence innovations (Straus 1991, 1993; Zilhão 1997; Bicho and Haws 2008; Bicho et al. 2011, 2017a; Cascalheira et al. 2017; Baker et al. 2024).

These innovations are believed to have resulted from human adaptations and resilience to the shifting conditions of the Late Pleistocene, which was marked by abrupt climatic events such as the Heinrich events and the Last Glacial Maximum (LGM) (Sanchez Goñi and Harrison 2010). These climatic shifts had a profound impact on flora and fauna, with exception of spatially limited refugia, likely disrupting settlement patterns and the organisation of hunter-gatherer groups, ultimately leading to a process of cultural reorganisation (Morin 2008; Bradtmöller et al. 2012; Schmidt et al. 2012), which has frequently been a focus of UP research.

In particular, the Iberian Peninsula has been recognised as a key region for studying UP adaptations and cultural transitions (e.g., Zilhão 1997, 2021; Gamble et al. 2004; Finlayson et al. 2006; Jiménez-Espejo et al. 2007; Bicho et al. 2011, 2017b; Jennings et al. 2011; Bradtmöller et al. 2012; Schmidt et al. 2012; Cascalheira and Bicho 2013; Aubry et

✉ Joana Belmiro
jfbelmiro@ualg.pt

¹ Interdisciplinary Center for Archaeology and the Evolution of Human Behaviour, University of Algarve, Faro, Portugal

² Spanish National Research Council - Institute Milá y Fontanals of research on Humanities, Barcelona, Spain

al. 2016, 2022; Cascalheira et al. 2017, 2021; Zilhão et al. 2017; Rasilla et al. 2020; Linscott et al. 2023). This significance is largely due to its location in southwestern Europe, which enabled it to maintain a relatively temperate climate even during the coldest periods, such as the LGM. As a result, the Iberian Peninsula served as one of Europe's most important glacial refugia (Hewitt 2000; Gómez and Lunt 2007; González-Sampériz et al. 2010; Jennings et al. 2011; Schmidt et al. 2012).

These refugia provided stable environments that were continuously occupied by hunter-gatherers, leading to the formation of eco-cultural niches—stable socio-ecological systems where human settlements were recurrent, and cultural adaptations were shaped by ecological constraints and opportunities (Cascalheira et al. 2017). These eco-cultural niches present a unique opportunity to examine long-term dynamics in resource exploitation, offering valuable insights into human adaptive strategies in response to cultural and social transformations.

More specifically, southwesternmost Iberia has been identified as a key eco-cultural niche for studying cultural transitions and the role of this peripheral coastal region within hunter-gatherer social networks. This is mainly due to the archaeological site of Vale Boi, the only site in southwestern Iberia with a nearly complete UP sequence, making it a crucial reference for examining long-term technological and mobility patterns in the region (Cascalheira et al. 2017). Its well-preserved stratigraphic continuity allows for a detailed analysis of cultural and technological trends across different phases of the UP.

Research at Vale Boi has provided valuable insights into hunter-gatherer subsistence strategies and technological organisation (Manne et al. 2012; Bicho et al. 2013, 2017b; Marreiros et al. 2015; Pereira et al. 2016a, b; Horta et al. 2019; Cascalheira 2019; Belmiro et al. 2021), and lithic technology studies from this site have highlighted the region's shifting and complex role within the broader territorial landscape.

In this context, comparisons between Vale Boi and the Gravettian occupations in central Portugal and southern Spain revealed marked regional differences, suggesting more limited movement of people and information in southwestern Iberia. These differences were suggested to be related to Vale Boi's peripheral location and the distinct ecological characteristics of westernmost Algarve (Marreiros and Bicho 2013). In contrast, Proto-Solutrean evidence from the site indicates technological similarities and strong connections with central Portugal (Belmiro et al. 2021), while the Solutrean period stands out as a highly dynamic phase at Vale Boi, during which the site functioned as a key connection point between central Portugal and southern

Spain, facilitating social networks and cultural exchanges (Cascalheira 2013; Bicho et al. 2017b).

Expanding on these findings, recent research has further refined our understanding of mobility and social networks through lithic raw material studies at the site. Our team's recent work identified non-local cherts originating from central Portugal and southern Spain in the UP lithic assemblages of Vale Boi (Belmiro et al. 2025). The proportions of these materials varied throughout the UP with earlier occupations (Gravettian) showing high frequencies of non-local chert, while later phases (Proto-Solutrean and Solutrean) exhibited a marked decline. These findings suggest the establishment and maintenance of extensive social networks connecting southwestern Portugal to southern Spain and central Portugal as early as the beginning of the UP.

While previous studies have explored Vale Boi's technological organisation, a direct analysis of how raw material sourcing shaped lithic production strategies remains missing. This study bridges that gap by examining chert procurement in relation to tool production, use, and discard, providing critical insights into hunter-gatherer mobility, settlement strategies, and social interactions across Iberia.

This paper presents a combined analysis of lithic technology and raw material sourcing, aiming to refine our understanding of technological and social adaptations throughout the UP in southwestern Iberia. By integrating archaeological and ethnographic perspectives, we test expectations regarding the organisation of hunter-gatherer technological systems and their implications for mobility, resource management, and social interactions. In doing so, we contribute to ongoing discussions about eco-cultural niches and the role of southwestern Iberia within broader UP social networks.

Theoretical framework and objectives

Lithic technological organisation has long been a central focus in archaeology, offering critical insights into past human behaviour and adaptive strategies. It encompasses all stages of stone tool production and use, from raw material acquisition to discard. Nelson (1991) defines it as the selection and integration of strategies for tool production, use, transport, and maintenance, while Kelly (1988) emphasises its spatial and temporal dimensions within cultural systems. These perspectives highlight the interrelationship between raw material sourcing, mobility, and settlement organisation—key factors in understanding hunter-gatherer adaptations.

Raw material procurement is a fundamental aspect of lithic technological organisation, as it played a crucial role in the lives of past hunter-gatherer groups by determining the possibilities for tool production and use (Bamforth and Bleed 1997). Approaches focused on the study

of raw materials provide key knowledge on several topics of hunter-gatherer organisation such as procurement and mobility strategies (Binford 1979; Gramly 1980; Binford and Stone 1985; Gould 1985; Ambrose and Lorenz 1990; Kuhn 1991; McCall 2007), occupation types and their duration (Torrence 1983; Kuhn 2004; Surovell 2009; Grove et al. 2023), and social networks and exchanges (Gamble 1999; Whallon 2006). However, raw material studies often focus on the characterisation of geological and archaeological raw materials to identify local and non-local raw materials within an assemblage, their possible sources, and examine their proportions within a site over different occupations and periods.

While distance to source and raw material proportions offer valuable insights, they represent only one aspect of raw material procurement and management. A raw material-focused approach alone is insufficient for comprehensively understanding mobility patterns and technological organisation. Numerous studies and models from both ethnographic and archaeological perspectives have demonstrated the complex interplay between lithic technological variability, raw material provisioning, and mobility. This has allowed the identification of several patterns and the development of hypotheses concerning these topics, which may be tested and aid in interpreting data from specific sites and lithic assemblages.

For example, technological variability within a lithic assemblage may be explained by the abundance and quality of raw materials (Andrefsky 1994; Brown 1999; Oestmo 2017). Archaeological studies from varied geographical regions such as western North America, Greece and Portugal have shown that when raw materials in proximity to a residential site are abundant and of good quality, a high percentage of formal tools are produced (Perlès 1992; Andrefsky 1994), and artefacts show less reduction intensity and decreased conservation through retouching (Thacker 2002). When local raw materials are scarce or of low quality, non-local resources are procured to produce mostly formal tools (Perlès 1992; Andrefsky 1994). Similarly, when groups move to areas where raw material is scarcer or of poorer knapping quality, more effort is placed into the preparation of transportable cores and the production of tools (Kelly 1988).

However, the different patterns between local and non-local raw material proportion and use in lithic assemblages may be less obvious whenever prehistoric groups have easy access to non-local raw materials due to high mobility or exchanges between groups (Ericson and Earle 1982; Torrence 1986; Brown 1999; Akerman et al. 2002; Oestmo 2017). Furthermore, Roth and Dibble (1998) demonstrate that even in areas where good quality raw material is abundant, non-local raw materials were still transported to the

site, often in the form of large blanks or trimmed cores, and both local and non-local raw materials were retouched into tools.

Tools, flakes and cores often functioned as portable sources of raw material within mobile toolkits or during non-local raw material procurement, enabling stone knapping during periods of limited time or in environments with scarce or unsuitable materials (Gould et al. 1971; Shott 1986; Kelly 1988; Perlès 1992; Kuhn 1994; Morrow 1996). In this context, the transport of formal cores (e.g., blade cores) and bifaces used as cores have been interpreted as lightweight and reconfigurable raw material storage strategies (Clark 1987; Kelly 1988).

Formal tools and the degree of tool maintenance have also been associated with planned preparation, efficient use, and transportability, reflecting their connection to mobile settlement strategies, short-term site occupations (Torrence 1983) and the regional distribution of raw materials (Bamforth 1986). In some cases, non-local raw materials, transported as part of personal toolkits (frequently associated with residential mobility), would primarily arrive at sites as retouched pieces (Kuhn 2004). These artefacts would show higher degrees of reduction and reworking (Kuhn 2004) and a higher percentage of non-cortical flakes (Roth and Dibble 1998), as they would have been in use for an extended period before being discarded. When knapped on-site, non-local materials also tended to exhibit higher proportions of retouched tools compared to local materials.

Tool variability and size may also be impacted by mobility and uncertainty regarding raw material availability: increased group mobility may create a pattern of limited tool variability, and tools may become less specialised and easily reconfigurable, such as retouched blanks (Odell 1981; Siegel 1984; Shott 1986). Increased mobility also often results in smaller tools (Shott 1986), although other authors have noted that large tools may be well-suited to a mobile lifestyle due to their extended use-life, allowing them to remain functional in areas where raw materials are scarce or unsuitable for knapping (Morrow 1996).

The proportions of local vs. non-local raw materials discussed thus far have focused greatly on group mobility, which is linked with residential mobility and occupation duration. Residential mobility (e.g., foraging range size and frequency of residential moves) is a defining characteristic of hunter-gatherer societies and plays a central role in their lifeways (Kelly 1995). It is a key factor driving changes in lithic assemblages (Roth and Dibble 1998; Brown 1999; Oestmo 2017) as it significantly impacts the cost and use of artefacts and raw materials since they affect the relation between the distance of raw material sources to sites (Kuhn 2004). As such, different raw material and technological

patterns have been observed between short-term and long-term occupations.

Short-term occupations have been observed to typically rely on transported (non-local) toolkits (Torrence 1983) and raw materials (Surovell 2009), show higher reduction intensity, and an increased tools-to-debitage ratio in the assemblages (Grove et al. 2023). In comparison, long-term occupations may rely on provisioning sites with locally available and suitable raw materials, while non-local materials are gradually used and discarded (Surovell 2009; Grove et al. 2023). Non-local raw material cores have been observed to be highly reduced and extensively exploited (Roth and Dibble 1998; Kuhn 2004) and exhibit higher blank-to-core ratios (Roth and Dibble 1998).

Altogether, different studies highlight significant variability in lithic assemblages and raw material proportions, reflecting different facets of hunter-gatherer technological organisation. This variability appears between behaviourally and ethnically similar sites (Bamforth 1986), across distinct chrono-cultural periods, and even within a single site among various raw materials. To fully understand past hunter-gatherer behaviours, organisation, and lifeways, it is crucial to examine all stages of lithic production—procurement, distribution, use, maintenance, and discard—through interconnected approaches that combine lithic technology and raw material analyses.

This study aims to refine our understanding of lithic resource provisioning, use, and management strategies among the UP hunter-gatherer groups settled at Vale Boi. To examine the role of chert procurement and reduction strategies at Vale Boi we test several expectations and hypotheses derived from the previously mentioned studies and models about raw material use and lithic technology organisation, focusing mainly on the different management of local and non-local raw materials, associated with mobility and

occupation length, which are summarised in Table 1. These expectations are tested through the comparison of local and non-local chert technological and metric characteristics, and used as heuristic devices to allow their comparison with the observed patterns at the site of Vale Boi and establish possible interpretations.

Materials and methods

Site description

Vale Boi is located on the western coast of the Algarve region, southern Portugal, at a latitude of N 37°5'24.1" and longitude of W 8°48'32.4" (Gibaja and Bicho 2006; the original site coordinates were converted from Degree/Minute to Degree/Minute/Second), within a small valley extending ~2 km southward to the Atlantic Ocean (Fig. 1a). The site is nestled among limestone outcrops that create west- and southwest-facing rock shelters (Fig. 1b). Covering more than 10,000 square meters along the valley slope, Vale Boi includes three main excavated areas, Slope, Terrace, and Shelter (Fig. 1c), which were excavated between 2000 and 2019 (Bicho et al. 2007, 2012, 2013; Manne et al. 2012; Cascalheira and Bicho 2013; Cascalheira et al. 2017). Based on the available raw material and technological evidence, particularly the macroscopic and petrographic data (Belmiro et al. 2025), the Terrace and Shelter areas were selected for the current study.

The Terrace area preserves occupations ranging from the UP to the Early Neolithic. While excavations started in 2000, an additional 8-square-meter trench was opened in 2012 to refine the stratigraphic sequence and assess the presence of earlier UP deposits. Between 2012 and 2016, eight continuous primary litho-stratigraphic units were identified. The top layer of the Terrace is highly disturbed by agricultural works and followed by Neolithic and Epipaleolithic occupations. The latter can be found at the top of level 3, followed by a continuous UP sequence, differentiated through the sediment characteristics (e.g., colour and grain, corresponding to numbers) and cultural horizons (e.g., 4E and 5 attributed to the Proto-Solutrean based on the lithic technology and radiocarbon dating, corresponding to letters within the geological levels) (Belmiro 2020). The UP sequence includes multiple occupations, spanning ~10,000 years: Gravettian (levels 8 to 6) dated between approximately c. 32 and 27 ka cal BP, Proto-Solutrean (levels 5 to 4E) between approximately c. 26 and 24 ka cal BP, and Solutrean (levels 4D, 4 C, 4, and Lower 3) between approximately c. 24 and 20 ka cal BP (Cascalheira et al. 2013a, 2017; Belmiro et al. 2021).

Table 1 Expected results of the technological and metric comparison between local and non-local cherts based on the interpretations and hypotheses of previously mentioned archaeological and ethnographic studies

1. Local raw materials	2. Non-local raw materials
1a) Low use-lives, with knapping strategies characterised by manufacture, use and discard	2a) Majority of formal tools, in the case of individual provisioning or higher use-lives, with knapping strategies characterised by the manufacture, use and maintenance
1b) Decreased reduction, larger cores and debitage, lower blank-to-core ratio	2b) Increased reduction, smaller cores and debitage, higher blank-to-core ratio
1c) Decreased tool reworking, low presence of retouch and/or tool maintenance, and lower tool-to-debitage ratio	2c) Increased tool reworking, high presence of retouch and/or tool maintenance, and higher tool-to-debitage ratio
1d) Higher tool typology diversity	2d) Lower tool diversity, characterised by less specialised tools

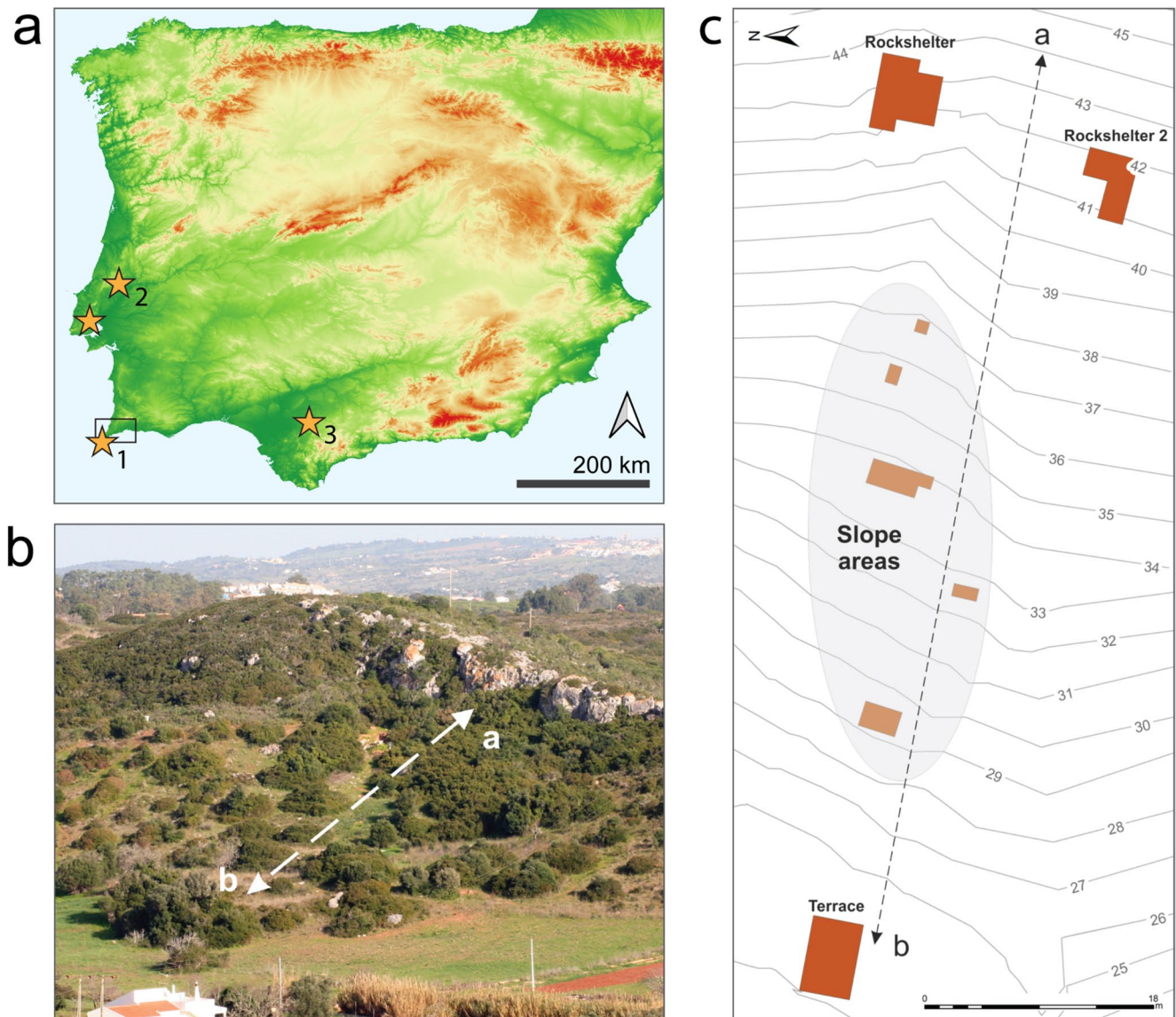


Fig. 1 **a**) Location of the archaeological site of Vale Boi (black box) within the Iberian Peninsula and approximate source locations of cherts identified in the UP sequence of Vale Boi: (1) local Lower Jurassic (C arixian) chert formations, (2) Cretaceous formations of central Portugal, in specific the Lisbon (bottom star) and Rio Maior (top star)

areas, (3) Upper Jurassic formations of the Betic Systems; **b**) photo of the limestone hill with terrace and shelter locations; **c**) schematic of the site area. Figures **b-c**) were adapted from Cascalheira et al. 2017. Figure **a**) was produced with resource to the open-source software QGIS (<https://qgis.org/>)

The Shelter area contains four main lithostratigraphic units, with occupations from the Magdalenian, Solutrean, and Gravettian periods. The Magdalenian and Gravettian levels (Z and D, respectively) were partially eroded, while the Solutrean levels represent the most intensive occupation, with three well-preserved archaeological horizons (layers A to C), dated to approximately c. 24–22 ka cal BP. These occupation levels were found beneath blocks of limestone that likely collapsed from the rock shelter ceiling, probably shortly after the LGM (Cascalheira 2010; Cascalheira et al. 2017).

The site's lithic assemblages represent all stages of stone tool production, with raw material use varying by occupation. Technological analyses of these assemblages have provided insights into the adaptive strategies of UP hunter-gatherers at Vale Boi, revealing technological shifts across different cultural phases. Given the chosen sample for this study (see Section Datasets and analysis), we summarise here the results for the technological analysis of the Solutrean assemblages (levels A-C) of the Shelter (Cascalheira 2010; Cascalheira et al. 2013b) and the Proto-Solutrean assemblages (levels 4E-5) of the Terrace (Belmiro 2020; Belmiro et al. 2021). The Gravettian occupations (levels

6–8) of the Terrace have been recently studied, but the results remain unpublished.

The lithic analysis of the Solutrean levels from the Shelter (levels A–C) shows a high number of lithic artefacts, with over 22,000 artefacts analysed (including chips which correspond to ~60% of the assemblage and shatter ~17–19%). The volumes introduced into the site were mostly cortical, given the high frequencies of cortex in blanks and retouched tools. The knapping strategies are dominated by unidirectional and bidirectional prismatic cores, with frequent core maintenance products. Flakes dominate the debitage assemblage, and endscrapers, notches, splintered pieces and retouched blanks are the most common retouched tools. Stemmed and winged points, laurel leaves, and shouldered points were also identified (Casalheira 2010; Casalheira et al. 2013b).

The Proto-Solutrean horizons yielded more than 26,500 artefacts (including chips which correspond to ~65–70% of the assemblage and shatter ~20%), ~11,000 attributed to the bottom of Terrace's level 5, and ~15,600 attributed to the top of level 5 and level 4E. Both horizons are characterised by knapping strategies dominated by unidirectional prismatic cores, with little platform preparation, focused on the obtention of bladelets (in bottom level 5) and flakes. Retouched tools are dominated by splintered pieces, endscrapers and retouched blanks, with Vale Comprido points (the Proto-Solutrean fossil director) being barely inexistent in chert and mostly produced in dolerite (Belmiro et al. 2021).

Previous studies showed that the main raw materials used at the site are chert, quartz, greywacke and smaller amounts of chalcedony, with the percentages of these changing across occupations. Notably, the lower Proto-Solutrean levels show high frequencies of quartz (Belmiro et al. 2021), whereas chert becomes the dominant raw material in the Solutrean occupations of the Shelter (Casalheira 2010). Likewise, different raw materials appear to have been used for specific purposes, with chert being particularly associated with the production of high percentage of blanks and retouched tools, and greywacke being extensively used for anvils (Horta et al. 2019).

Quartz and greywacke are locally available from streambeds near the site, whereas regional chert and chalcedony sources lie further afield, within a ~20 km radius (Pereira et al. 2016a, 2016b). Our previous studies showed, as expected, the existence of local cherts in the assemblages (Fig. 2a), originating from the Lower Jurassic (cherts) and Triassic (chalcedony) outcrops in proximity to the site (Fig. 1a1) (Belmiro et al. 2025). Despite petrographic differences between cherts and chalcedony, for this study any chert varieties (e.g., chalcedony or jasper) are referred to as chert (Luedtke 1978). A significant portion of non-local cherts was also identified (Fig. 2b–c), with some identified

sources, such as the Cretaceous outcrops of central Portugal (Lisbon and Rio Maior areas, Fig. 1a2) corresponding to the T6 cherts (Fig. 2b) and the Upper Jurassic oolitic/peloidal cherts of the Betic Systems in southern Spain (Fig. 1a3), corresponding to the T7 cherts and possibly the T9 cherts (Fig. 2b). This indicates varying degrees of contact or long-range mobility throughout the UP, likely influenced by shifts in settlement patterns and the duration of site occupation.

Previous research suggests that both the Terrace and Shelter functioned as seasonal residential camps, repeatedly occupied for extended periods by culturally resilient groups of hunter-gatherers (Tátá et al. 2014). This interpretation is based on high-density lithic assemblages, evidence of tool manufacture, diverse faunal remains (marine and terrestrial) and subsistence practices, personal ornaments and portable art (Manne et al. 2012; Tátá et al. 2014). Subsistence patterns and faunal analysis have been key for understanding seasonality, as the presence of neonate bones in combination with adult remains suggests an occupation during spring and early summer (Manne 2010). The faunal analysis also shows continuity through the UP with red deer, horse and rabbit (Manne and Bicho 2011), marine shells albeit with a small reduction during the Solutrean, possibly related to coastline distance changes (Manne et al. 2012), and the persistent use of techniques such as grease rendering associated with heat-cracked rocks (Manne and Bicho 2011). This residential occupation and continuity have been identified in most of the UP occupations, although with some exceptions.

Casalheira et al. (2017) applied the Whole Assemblage Behavioural Index (WABI) (Riel-Salvatore and Barton 2004; Riel-Salvatore 2010) to reconstruct and compare mobility strategies at Vale Boi. This method assumes that residential or logistical mobility can be discerned by the relation between the lithic volumetric density of an archaeological horizon and the frequency of retouched tools. By analysing lithic volumetric density and retouched tool frequencies from the Shelter's Solutrean (Casalheira 2010; Casalheira et al. 2013b) and Magdalenian (Mendonça 2009) levels, as well as the Terrace's Gravettian levels (Marreiros et al. 2015), the authors noted that most occupations were composed of high-density assemblages with low degree of retouch. Technological data from the site also noted that the occupations were also mainly characterised by expedient technological patterns. These were interpreted as the result of long-term residential base camps, except for the Early Gravettian and Magdalenian occupations which showed low-density and high degree of retouch, thus possibly the result of logistical, short-term camps. Regarding the Terrace area, however, the results were based on previous excavations (<2012), and the identification of new layers and reorganisation of the occupations is yet to be tested through the use of lithic techno-typological methods.

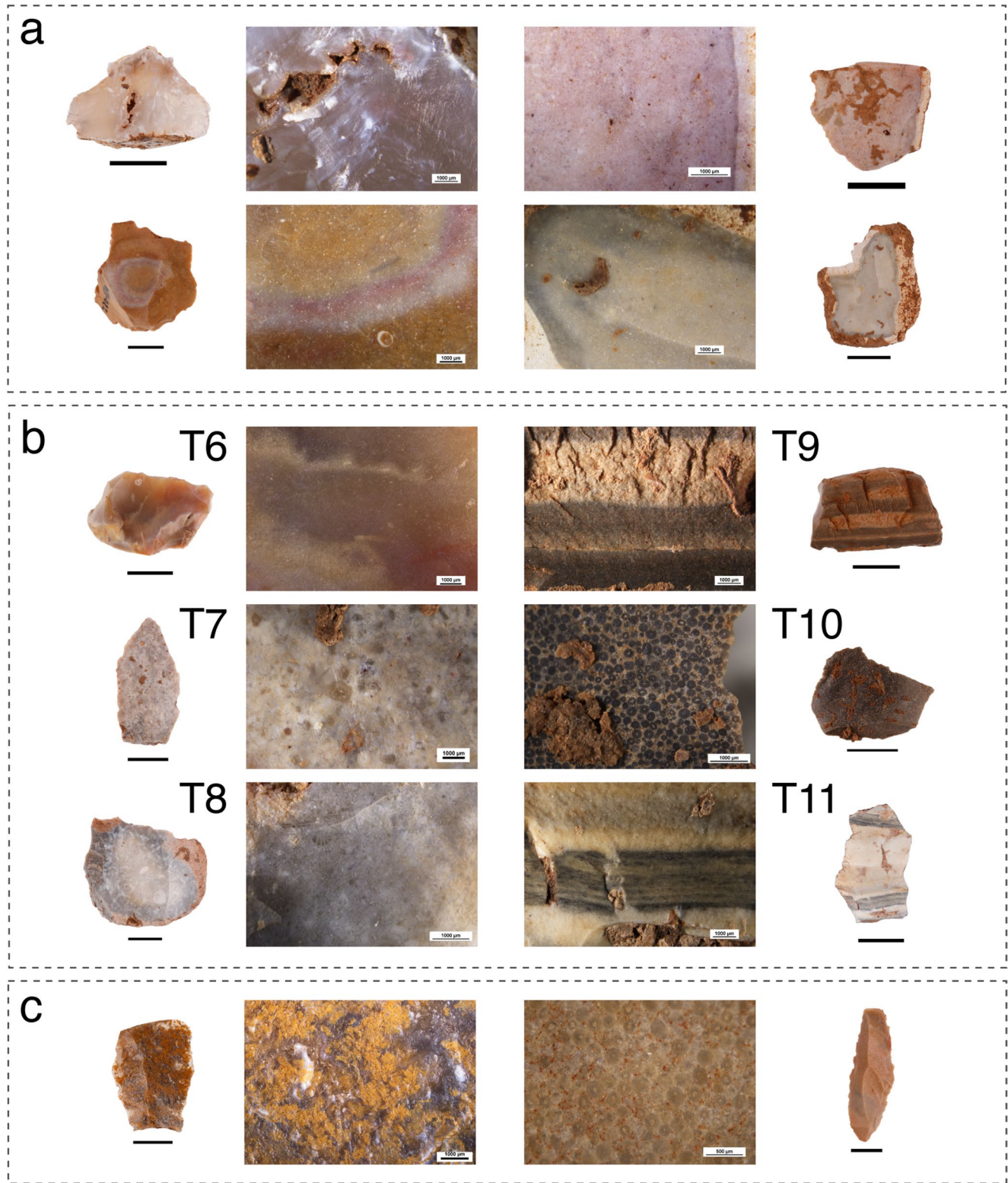


Fig. 2 Simplified scheme of chert types identified in the UP sequence of the terrace and shelter areas of vale boi: (a) local chert macroscopic variability (T1 to T5), including chalcedony (T1; top left); (b) non-local chert types present in all occupations except for T11 which is

only present in the Solutrean; (c) TL09 (left) and TL06 (right) varieties within the trace lithologies group (TL) composed of non-local cherts with 1–3 samples per TL type and limited to specific archaeological levels and areas. Summarised from Belmiro et al. (2025)

A similar conclusion was suggested based on the interpretation of the chert sourcing and proportions in the several UP occupations of the Terrace and Shelter of Vale Boi and following other models relating local/non-local raw materials with mobility (Surovell 2009; Grove et al. 2023). The Gravettian occupations (levels 6 and 7) showed high proportions of non-local chert (~50%), with a gradual reduction in the following occupations. This high frequency of non-local cherts was unexpected, as previous studies focusing on technology had identified key typological differences between different regions, suggesting a Vicentine facies (Marreiros et al. 2015). This regionalisation was interpreted as either ecological adaptations or as a cultural/geographical divide between central Portugal, southwestern Portugal and Mediterranean Spain, strengthened by the identification of culturally resilient behaviours across all the UP at Vale Boi (Manne et al. 2012, 2014; Tátá et al. 2014), weakening interpretations related seasonal group mobility across long distances from elsewhere to Vale Boi. Instead, the high frequencies of non-local chert were interpreted as a possible result of settlement changes. In this sense, possibly through exchanges with other groups, Gravettian groups obtained long-distance raw materials which were transported to the site of Vale Boi, where the short-term character of the occupation with frequent moves led to the exploitation of the transported cherts and less necessity to heavily rely on local cherts. The following occupations were interpreted as residential, long-term occupations with more infrequent moves, where the transported cherts would be exploited but reliance on local cherts would increase due to less mobility, leading to an increase in frequency when compared to non-local cherts (Belmiro et al. 2025).

Datasets and analysis

The current study focuses on the correlation between the techno-typological analysis and the geoarchaeological study of the chert lithic assemblages of the UP of Vale Boi. It integrates previously collected datasets, which have been published or are openly accessible in online repositories, allowing for transparency and reproducibility.

The macroscopic and petrographic data of cherts was previously collected and published by our team (Belmiro et al. 2025) and can also be found in an online repository (<https://www.https://doi.org/10.17605/OSF.IO/DBFT2>). This study focused on the UP chert assemblages of Vale Boi, especially the Gravettian (levels 6 and 7), Proto-Solutrean (levels 4E and 5) and Solutrean (levels 4 to 4D) from the Terrace area and the Solutrean (levels A to C) from the Shelter area. The full methodology used in the study, dataset and supporting documents can be found in the article and the

online repository. We present here the summarised methodology used in the study.

The macroscopic analysis was done with resource to a hand lens followed by observation under a stereomicroscope (Nikon SMZ25), to identify chert types based on characteristics such as colour, lustre or the presence/absence of inclusions and fossils, according to other studies and specialised literature. Other characteristics such as the type of cortex and the presence of alterations were also recorded. A following petrographic analysis of 22 thin sections were used to further characterise the chert types and solidify the validity of the macroscopic groups—thin sections were made of all major chert types identified in the Terrace area with the goal of obtaining several thin sections of heterogeneous chert types. The thin section analysis was carried out using a polarised light microscope (Nikon LV100ND) and focused on the identification of texture, orthochem composition, presence of allochems and bioclasts, porosity and other existing structures, following specialised literature. The data dictionaries used for these analyses can be found in their original research compendium (<https://doi.org/10.17605/OSF.IO/DBFT2>). The results were then compared with previous works by our team on geological samples using the same methodology (Belmiro et al. 2023) and on geological samples from the Cretaceous cherts of central Portugal, available in the LusoLit lithothèque at the ICAR-EHB laboratory and collected in previous prospection works (Pereira et al. 2016b). Samples from the Betic Systems, available at the Unit of Geoarchaeology and Archaeometry Applied to Historic Artistic and Monumental Heritage from the University of Cadiz (Spain) were also characterised through a macroscopic approach (stereomicroscope) and compared to the archaeological artefacts.

The Solutrean assemblage technological analysis was published by Cascalheira (2009) as part of a Master's thesis and following publications (e.g., Cascalheira 2010; Cascalheira et al. 2013b), with the study of levels A to C of the Shelter area. The dataset used for this study was not originally published but can be consulted in our online repository (<http://www.https://doi.org/10.17605/OSF.IO/UWMPK>).

The Solutrean analysis in this study is limited to the Shelter area due to the inexistence of technological studies for the better preserved Solutrean levels of the Terrace (e.g., level 4). However, and as seen in (Belmiro et al. 2025), the raw material patterns seem to show little differences between the Solutrean in both areas; coupled with the similar radiocarbon dates between the areas (c. 24–22 and 24–20 ka cal BP), we assume that they are representative of similar, long-term, residential occupations which aptly characterise the Solutrean groups of Vale Boi.

The Proto-Solutrean technological analysis was the result of a Master's thesis (Belmiro 2020) and following

publication (Belmiro et al. 2021), with the study of levels 4E and 5 of the Terrace area. The dataset and analysis can be consulted in the original online repository (<http://www.https://doi.org/10.17605/OSF.IO/456EG>).

Finally, the Gravettian technological analysis was the result of a recent and unpublished study, focusing on the chert lithic artefacts from levels 6 and 7 of the Terrace area (>2012 excavations). This dataset and preliminary technological analysis results can be found in our online repository (<http://www.https://doi.org/10.17605/OSF.IO/UWMPK>) and in Online Resource 1.

One challenge of integrating datasets collected by different researchers is variability in methodologies and recorded variables. However, this study minimises such inconsistencies by ensuring methodological alignment across datasets, as all data collection followed standardised attribute-based lithic analysis protocols, already described in previous publications (Belmiro et al. 2021; Cascalheira 2010) and available for consultation also in online repositories (see <https://doi.org/10.17605/OSF.IO/456EG> for the data dictionary used in Belmiro et al. 2021). An abridged data dictionary with variables used in this study (in the statistical analysis of previously collected data or used in the analysis of the Gravettian assemblage) can be found in Online Resource 2. The lithic analysis datasets used in this study adopted an attribute-based methodology, which aims to describe morphological and metrical attributes of technological classes. The attributes analysed followed those present in specialised literature, such as Brézillon (1968) and (Tixier et al. 1980), paired with other Palaeolithic lithic attribute analyses (e.g., Bicho 1992; Zilhão 1997; Tostevin 2012; Cascalheira 2019).

After data collection, the databases were imported into R Programming Environment, where the information was processed through the creation of descriptive statistical analysis and writing of this article. Some differences in the collection process, especially between the study by Cascalheira (2010) and the following studies, required homogenisation. For example, where in Cascalheira (2010) retouch was an independent variable (e.g., Class as flake, Retouch

as Yes), in Belmiro et al. (2021), retouch was identified as Class variable. In this situation, the Solutrean dataset was modified so that all artefacts with retouch were identified in the Class variable, instead of the original classification. All changes applied to the original data made for homogenisation between datasets can be consulted in the R Studio scripts in our online repository (<http://www.https://doi.org/10.17605/OSF.IO/UWMPK>).

To integrate technological and raw material data, we merged multiple datasets using the artefact identifier (“ID”), which corresponds to total station plot records. This identifier links artefacts to either precise excavation coordinates (for individually plotted pieces) or generalised spatial data (for sieved assemblages).

Given that the raw material analysis focused exclusively on individually piece-plotted artefacts (dimensions >2 cm or complete bladelets <2 cm), the final dataset does not include all excavated material but retains the most diagnostically relevant pieces for analysis. As a result, the final dataset used in this study does not directly correspond to the full datasets analysed in the original studies (Table 2). Similarly, the raw material study used only currently accessible artefacts from the assemblages. This is especially relevant for the Shelter Solutrean chert assemblage, where shatter is absent from the sample due to the lack of availability for study.

A limitation of this study is its reliance on a subset of the total lithic assemblage, which excludes small debris. While this may omit some aspects of on-site knapping activities, the analysed sample remains representative of the broader technological trends at Vale Boi throughout the UP sequence.

Following data homogenisation and integration, we conducted descriptive statistical analyses and non-parametric statistical analyses to examine correlations between raw material use and technological patterns and test expectations related to the technological organisation of local and non-local cherts (see Table 1), and between different UP occupations. To test these expectations, we evaluated 9 parameters for each dataset and assemblage; the parameters and their calculation/measurement methods are detailed in Table 3.

The entirety of the R code used for the analysis, datasets, and visual representations contained in this paper can be accessed through our online repository (<http://www.https://doi.org/10.17605/OSF.IO/UWMPK>). We used the rrtools package by Marwick et al. (2018) to create a research compendium and write a reproducible journal article. The provided files include the complete set of raw data used in the analysis, along with a custom R project (Wickham 2015) containing the code required to generate all tables and figures. To enable maximum reuse, the code is made available

Table 2 Sample absolute number comparison between original technological analysis datasets (chert and chalcedony only, excluding chips) for the Solutrean occupation of the Shelter area (levels A-C) published in Cascalheira (2010), the Proto-Solutrean occupation of the Terrace (levels 4E and top of 5) published in Belmiro et al., (2021) and the Gravettian occupation of the Terrace (levels 6-7) and the final datasets used in the study after filtering individually plotted IDs (excluding bucket points) and merging with the geoarchaeological dataset published in Belmiro et al., (2025)

Assemblage	Original dataset (n)	Merged dataset (n)
Shelter level A-C	3290	910
Terrace level 4E-5	1413	635
Terrace level 4E-5	781	766

Table 3 Analysis parameters used in the study, calculation/measurement used for each parameter, and unit of the parameter results after analysis. Parameters concerning size and ratios (P4-7) included only complete artefacts

Parameter	Calculation/Measurements	Unit
P1 - Frequency of retouched tools	N retouched tools / Total assemblage * 100	%
P2 - Frequency of cores	N cores / Total assemblage * 100	%
P3 - Frequency of maintenance products	N maintenance products / Total assemblage * 100	%
P4 - Debitage sizes	Length, Maximum Width, Weight	mm
P5 - Tool to debitage ratio	N tools / N debitage	ratio
P6 - Core sizes	Length, Maximum Width, Weight	mm
P7 - Blank to core ratio	N blanks / N cores	ratio
P8 - Tool diversity	N of retouched typologies	N
P9 - Tool specialisation	N of retouched blanks vs other typologies	N

under the MIT license, data under CC-0, and figures under CC-BY (additional details can be found in Marwick 2017).

Results

Results are structured according to the predefined analytical parameters, comparing local and non-local cherts (Fig. 2) across different assemblages. A comprehensive description of each assemblage and detailed tables for all analyses are provided in Online Resource 1.

Blanks and blank fragments represent the most abundant lithic class in all assemblages, accounting for over 40% of artefacts across all chert types (Fig. 3; Online Resource 1, Tables s1, s4 and s6). Within complete blanks, flakes are the most frequent in all chert types and all assemblages (~25–45%; Fig. 3; Online Resource 1, Tables s1, s4 and s6), with elongated blanks (blades and bladelets) being present in smaller numbers (Fig. 3). As expected, cores are present in lower frequencies (~3–8%) but are more numerous in local cherts than in non-local types and absent from the TL group. In the Proto-Solutrean assemblage, non-local chert cores are rare, with only T7-9 yielding a small number ($n=4$ complete cores, $n=2$ core fragments; Online Resource 1, Table s4). Albeit in very small numbers ($n<10$) in the Gravettian and Solutrean assemblages, core preparation and maintenance products are also present in local and non-local cherts, especially in the non-local types which show the larger sample number, such as T6-7 (Fig. 3; Online Resource 1, Tables s1 and s6). In the Proto-Solutrean assemblage, core preparation and maintenance products are only present in non-local cherts and in very small numbers ($n=2$; Online Resource 1, Table s4). The presence of knapping by-products such as shatter is also seen in both local and non-local cherts in the Gravettian (Fig. 3a) and Proto-Solutrean (Fig. 3b) assemblages. Retouched tools are present in all

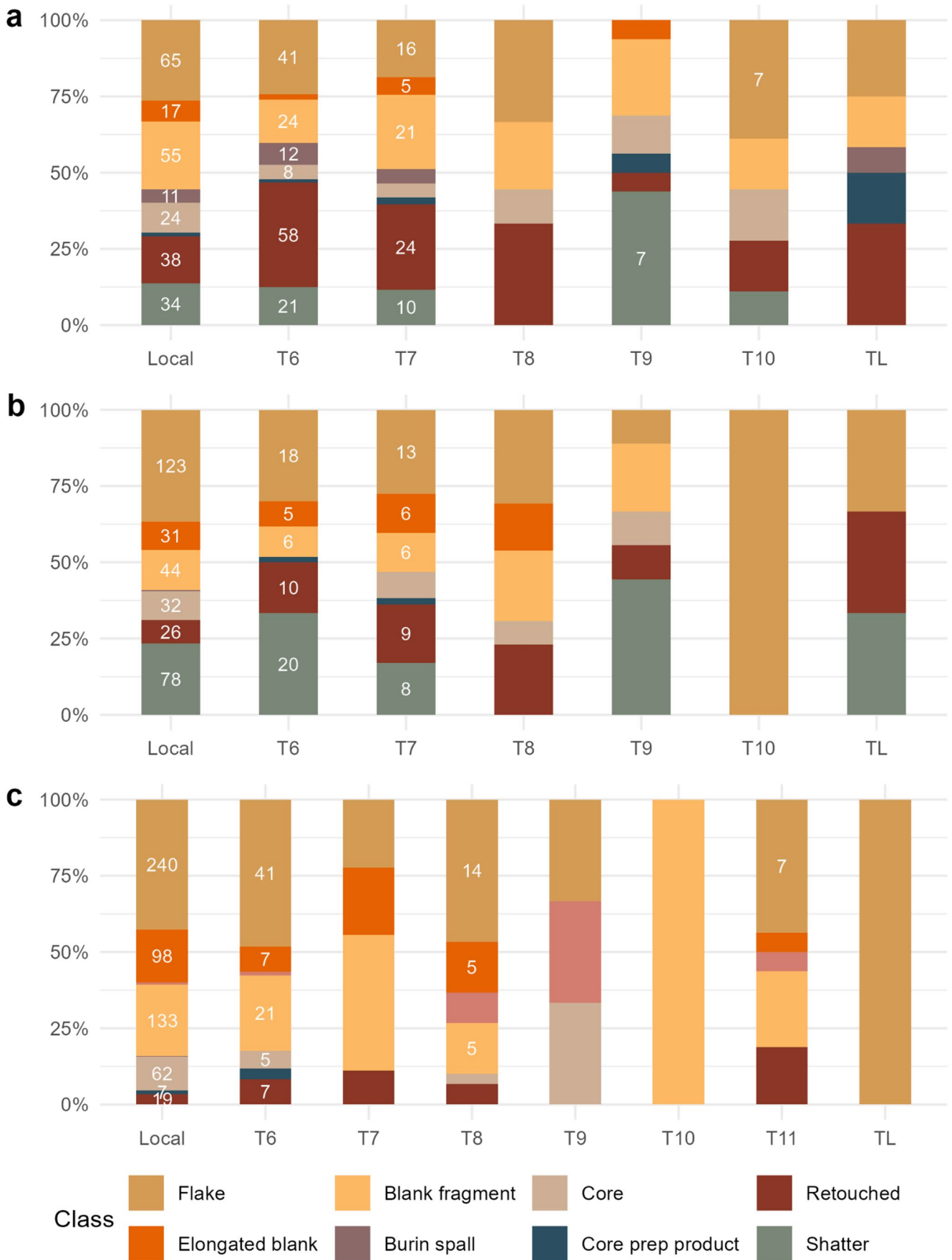
Fig. 3 Class by chert type in the Gravettian (a), Proto-Solutrean (b) and Solutrean (c) assemblages. Labels within the plots correspond to the number of artefacts within each class. Only labels of $n>4$ are shown

chert types across all assemblages. In general, local cherts exhibit lower retouch frequencies than non-local cherts, though the total number of retouched tools varies significantly between assemblages (Fig. 3; Online Resource 1, Tables s1, s4 and s6).

The Gravettian assemblage exhibits the highest proportion of retouched tools (~21%; Fig. 3a). Tool diversity is greater among non-local cherts, which contain a high frequency of generalised tools (e.g., notches, retouched pieces) alongside hunting implements such as backed bladelets (Online Resource 1 Table s3). The abundance of burins is also clear in the Gravettian assemblage, making up the most present retouched tool type ($n=54$), with an associated presence of burin spalls (~4%) in higher percentages than in other assemblages (Online Resource 1 Tables s1 and s3). In comparison to the Gravettian, other assemblages show smaller numbers of retouched tools (<10%, Fig. 3b and c). While in the Proto-Solutrean (Online Resource 1 Table s5) no significant difference was identified between local and non-local retouched tools, in the Solutrean assemblage (Online Resource 1 Table s7) both tool diversity and tool specialisation are higher in local cherts.

Retouched tools were further explored through the tools-to-debitage ratio (Fig. 4a, Online Resource 1 Table s8). In general, the results show that non-local chert types have higher tool-to-debitage ratios than local types, albeit with differences between assemblages. The Gravettian assemblage shows the highest tool-to-debitage ratios compared to the remaining assemblages; non-local cherts show ratios above 0.9, while local cherts show values below 0.5. In the Proto-Solutrean non-local cherts show ratios between 0.3 and 0.5, while local cherts show ratios below 0.3. This pattern is less clear in the Solutrean assemblage since the ratios are the lowest of all assemblages. Non-local cherts show ratios above 0.1 (with exception of T8) while local cherts show ratios below 0.1 (with exception of T1; Online Resource 1 Table s8 c).

Blank-to-core ratios were analysed across assemblages (Fig. 4b, Online Resource 1 Table s9). In all cases, local cherts generally exhibit lower blank-to-core ratios than non-local cherts, though variability in core sample sizes may influence these patterns. For the Gravettian assemblages, the results reveal that non-local cherts show ratios above 7 (with the exception of T10), while local cherts have ratios located below 4. The Solutrean assemblage also shows higher ratios for non-local cherts (>12), with local cherts showing ratios below 7. The Proto-Solutrean assemblage has most blank-to-core ratios below 10, except for non-local



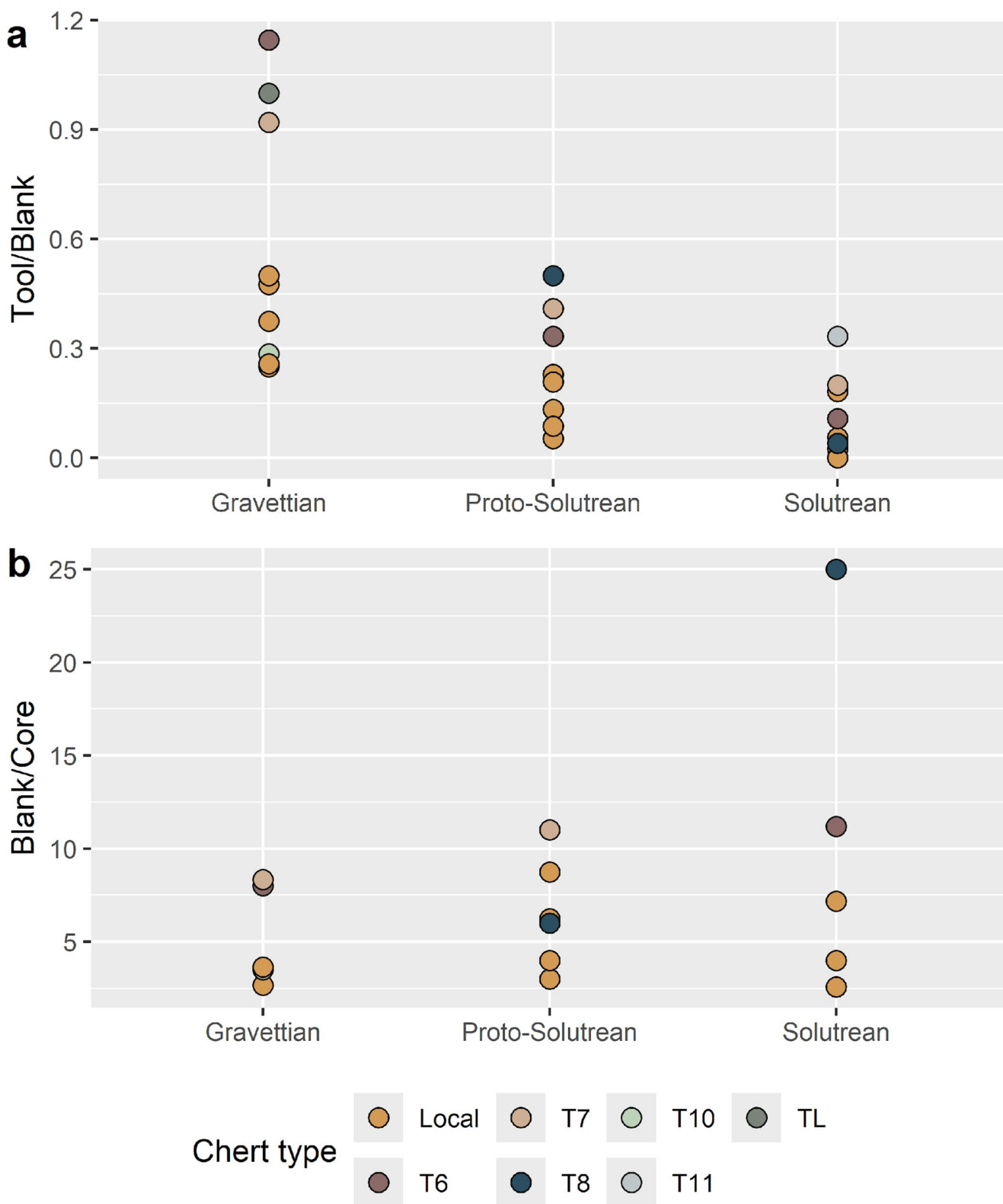


Fig. 4 Plotted ratios of tool-to-debitage (a) and blank-to-core (b) by assemblage (Gravettian, Proto-Solutrean and Solutrean) and by chert type. In both ratios, complete blanks (flakes and elongated blanks)

were included. All local cherts were grouped in a single category local, while non-local cherts maintained their individual types

T7. However, non-local cores are poorly represented within the assemblage (Fig. 4b, Online Resource 1 Table s4).

The sizes of flakes, elongated blanks and cores were explored through scatterplots of width and length (Figs. 5, 6 and 7a) and boxplots for weight (Figs. 5, 6 and 7b) and through non-parametric statistical tests; complete tables with descriptive statistics and non-parametric statistical test results can be found in Online Resource 1 Tables s10–12 and s13, respectively.

The scatterplots and boxplots show different patterns across the different classes. In the Gravettian assemblage (Fig. 5), non-local chert flakes are significantly smaller than local chert flakes in both length (<25 mm), width (<21 mm) and weight (<6 g), with *p* values of $4e-4$, 0.04 and $7e-3$, respectively (Online Resource 1, Table s13). While local chert flakes also cluster below 25 mm in width and length, they display greater variability and a higher number of outliers. The same patterns can be seen in the Proto-Solutrean assemblage (Fig. 6), where weight also shows statistically significant differences between chert types (0.01; Online Resource 1, Table s13), with non-local types showing smaller values. In comparison, in the Solutrean assemblage (Fig. 7), only non-local chert flake length seems to show statistically significant smaller values (*p* value of $1e-3$) than local flakes (Online Resource 1, Table s13), being mostly concentrated below ~30 mm, while local chert blank lengths are more variable.

For elongated blanks and cores, size and weight differences between local and non-local cherts are less pronounced than those observed in flakes. Regarding elongated blanks, it is clear that in the Gravettian assemblage, the largest number of artefacts is concentrated within what would be the bladelet classification (<12 mm in length). While not statistically significant, alike flakes, elongated blanks in non-local cherts show smaller measurements (Fig. 5; Online Resource 1, Table s10), especially T6 and T7 (<12 mm in width and <25 mm in length) when compared to local types, especially T2–5 (>17 mm in width and >30 mm in length). In the Proto-Solutrean and Solutrean occupations, there seems to be a slight increase in the size variability, making the presence of blades more pronounced than in the Gravettian assemblages (Figs. 6 and 7). Similarly to the Gravettian assemblage, the Proto-Solutrean and Solutrean elongated blanks show slightly smaller mean values in non-local cherts than in local cherts (Online Resource 1, Table s11 and s12), although none of the differences seem to be statistically significant (Online Resource 1, Table s13 b). It is key to note however, that the sample size for elongated blanks is much smaller than that of flakes (Fig. 3).

Regarding cores, in the Gravettian assemblage (Fig. 5), there is a cluster of non-local chert cores below the 25 mm width and length, while in general, local chert cores seem

to be more variable. Especially regarding weight, T6 cores (non-local) show lighter cores (~12 gr means) compared to local cherts (Online Resource 1, Table s10). In the Solutrean assemblage (Fig. 7), weight is the only measurement where differences can be seen between local and non-local chert cores; similarly to the Gravettian assemblage, T6 cores show slightly smaller cores (~18 gr means) than local cherts (~22 gr means; Online Resource 1, Table s12). Despite these differences, the statistical tests applied to the dimensions between local and non-local chert cores show no statistically significant differences between the groups ($p > 0.05$; Online Resource 1, Table s13). The Proto-Solutrean assemblage (Fig. 6) contains a limited sample of non-local chert cores ($n=4$), preventing clear pattern identification. However, as in other assemblages, local chert cores display a broad size range (~15–50 mm in width/length, ~3–85 g in weight; Online Resource 1, Table s11).

Following the analysis parameters, the results described above can be found in Table 4, and can be summarised as follows:

In the Gravettian assemblage, retouched tools (P1) are present in higher frequencies in the non-local cherts, as well as in core preparation and maintenance products (P3). Cores are present even in non-local chert types (P2). Debitage sizes (P4) show smaller sizes and weights for non-local cherts. Tool-to-debitage ratios (P5) are significantly higher in non-local cherts. Core sizes (P6) are slightly smaller in T6, a non-local chert, and the blank-to-core ratios (P7) are higher in non-local cherts. Tool diversity (P8) is higher in non-local cherts, although with high frequency of less specialised tools such as notches and retouched blanks, alongside burins and hunting implements such as backed bladelets (P9).

Compared to the Gravettian, the Proto-Solutrean assemblage contains fewer retouched tools (P1), with non-local cherts exhibiting slightly higher retouch frequencies. Non-local chert cores (P2) are rare, though evidence suggests knapping occurred on-site. Core preparation and maintenance products (P3) are only present in non-local cherts, albeit in very small numbers ($n=2$). Blank sizes (P4) and core sizes (P6) are slightly smaller in non-local cherts and elongated products seem to be more variable in size. Regarding the ratios, tool-to-debitage ratios (P5) are higher in non-local cherts, albeit smaller than those seen in the Gravettian assemblage, and blank-to-core ratios (P7) are also higher in non-local cherts. Little differences were observed in tool diversity (P8) and specialisation (P9) between local and non-local cherts.

Finally, the Solutrean shows no relevant differences in the frequencies of retouched tools (P1) and core preparation and maintenance products (P2) between local and non-local cherts, with only slightly higher frequencies in the non-local cherts. In general, the retouch frequency is lower than that

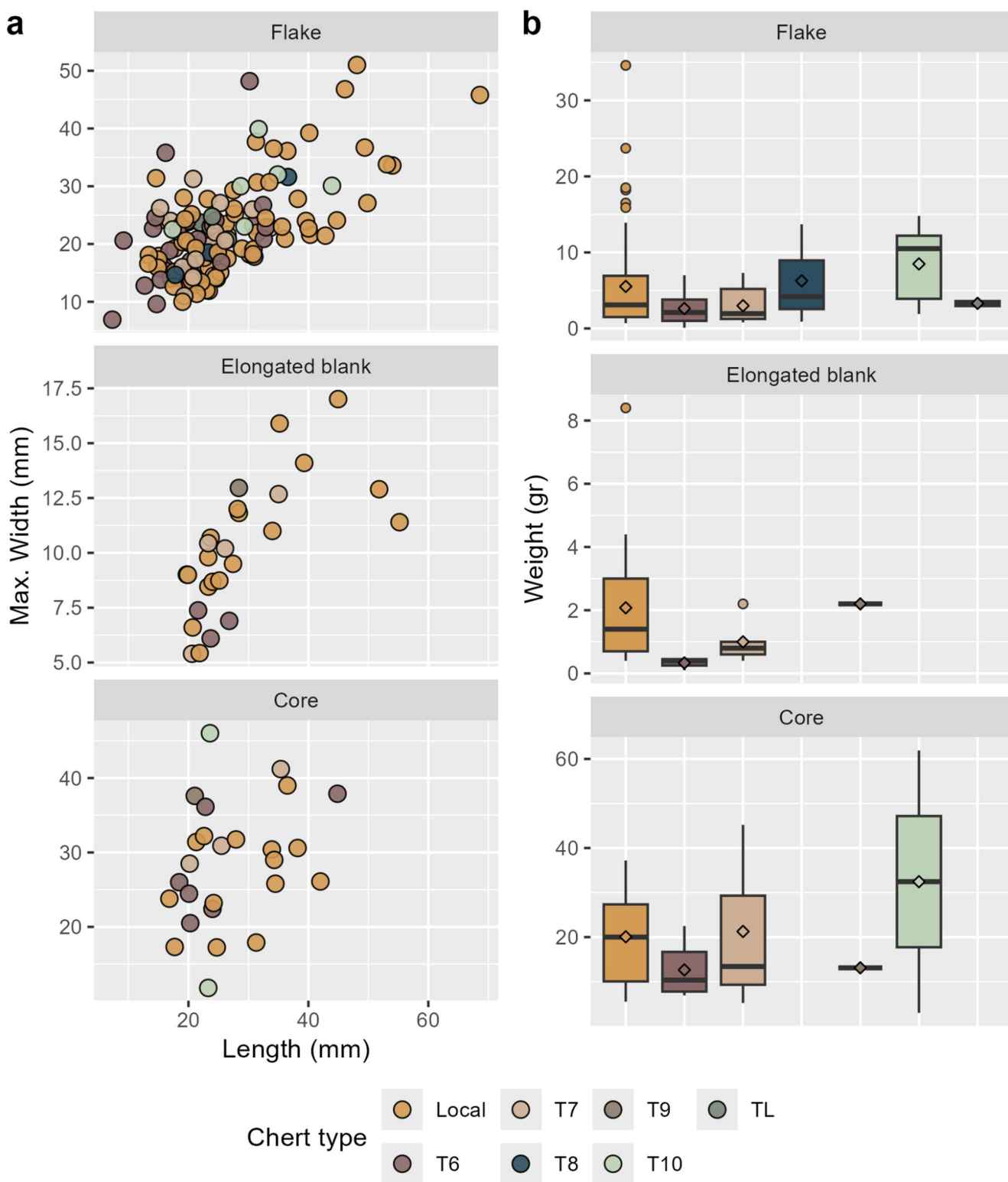


Fig. 5 Gravettian assemblage flake, elongated blank and core measurements and weight descriptive statistics in local and non-local chert types. **(a)** scatterplots of width and length. **(b)** boxplots of weight; diamond symbol represents mean values within each group

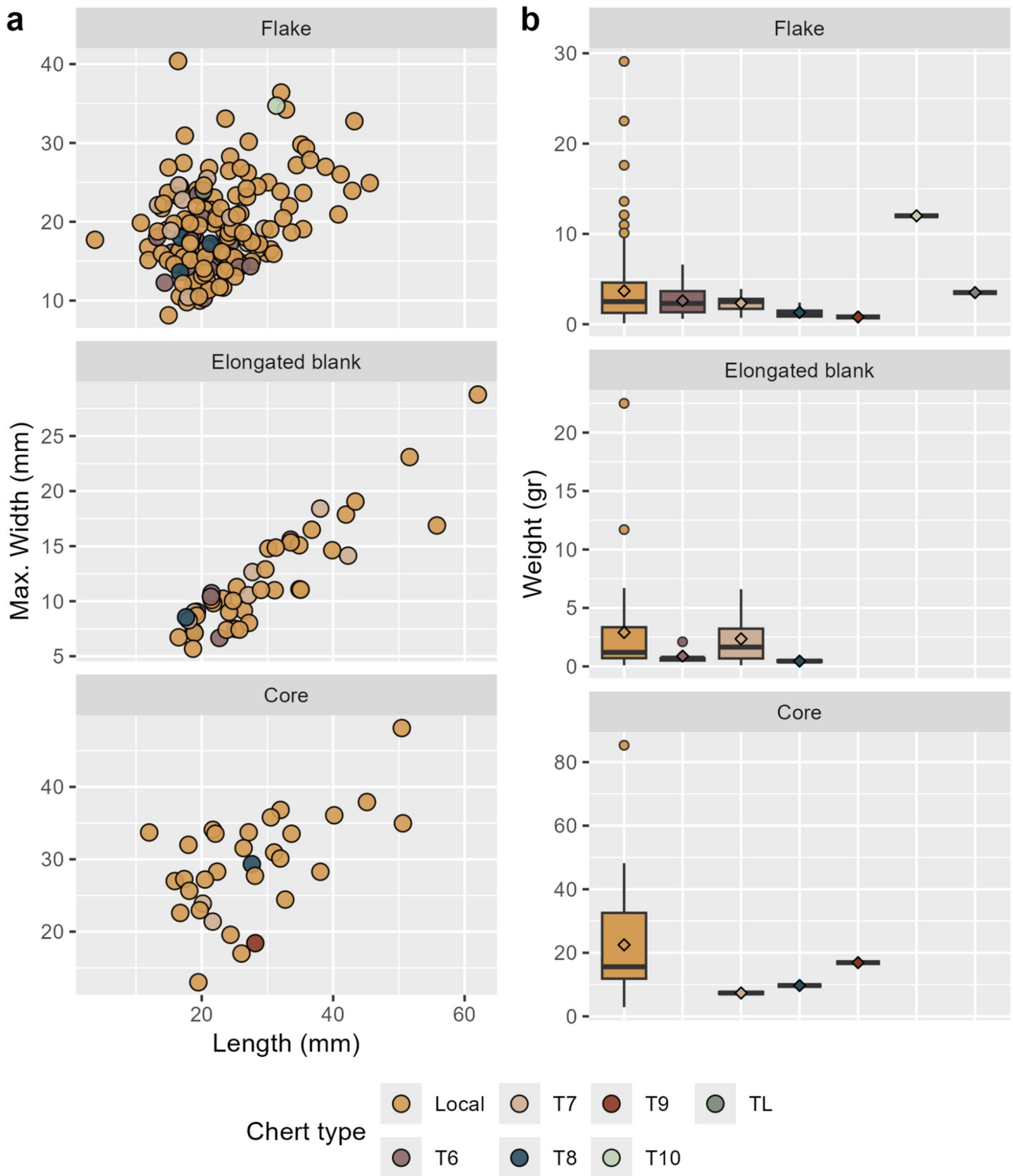


Fig. 6 Proto-Solutrean assemblage flake, elongated blank and core measurements and weight descriptive statistics in local and non-local chert types. **(a)** scatterplots of width and length. **(b)** boxplots of weight; diamond symbol represents mean values within each group

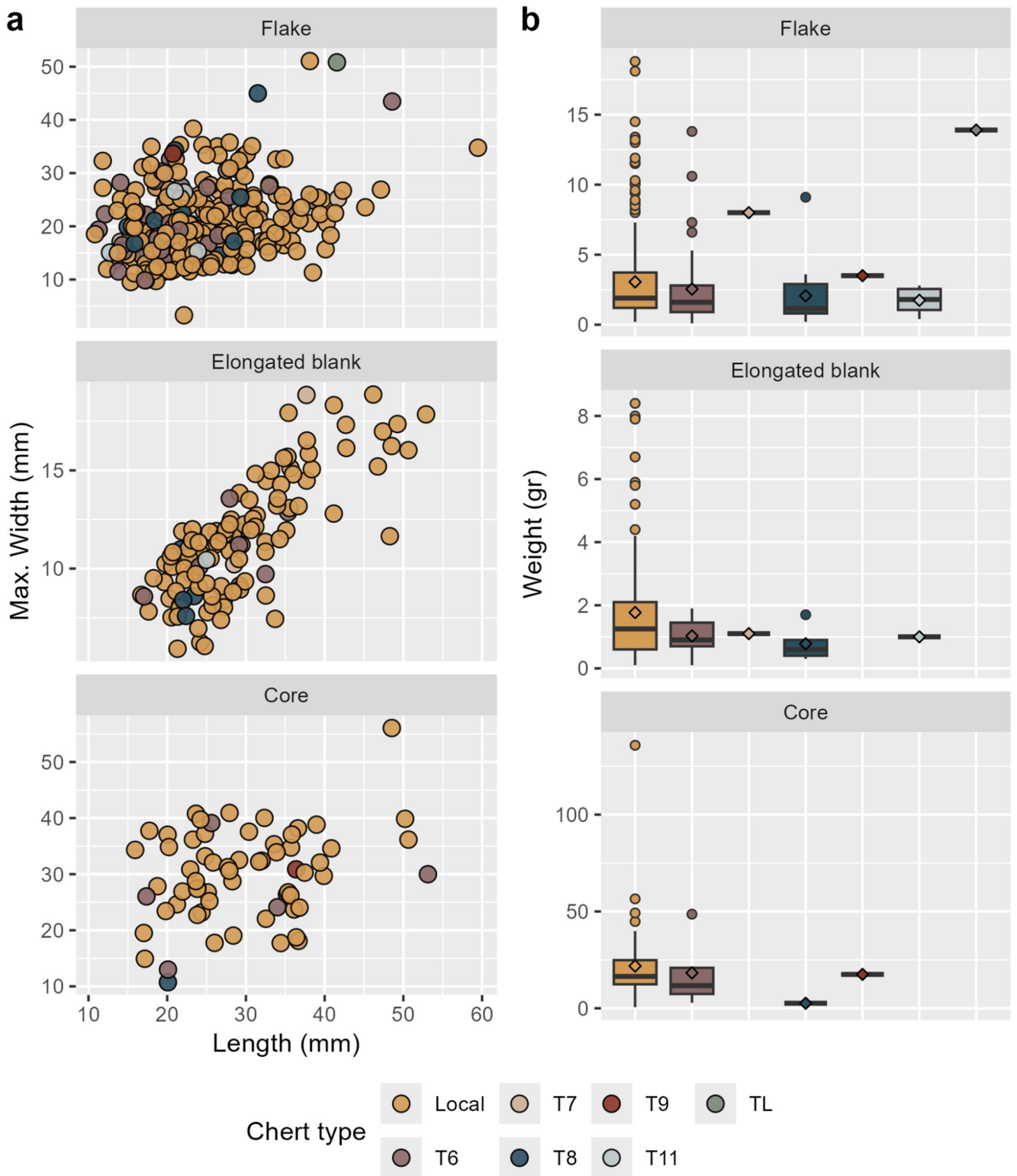


Fig. 7 Solutrean assemblage flake, elongated blank and core measurements and weight descriptive statistics in local and non-local chert types. **(a)** scatterplots of width and length. **(b)** boxplots of weight; diamond symbol represents mean values within each group

Table 4 Summarised results for analysis parameters between grouped chert types (local and non-local) by assemblage. Core sizes (P6) for the local proto-solutrean cherts are presented in mean values instead. * refers to the levels of significance from the non-parametric statistical tests: * significant p values (<0.05); ** very significant p values (< 0.01); *** highly significant p values (0.001)

Parameters	Gravettian		Proto-Solutrean		Solutrean	
	Local	Non-local	Local	Non-local	Local	Non-local
P1: Retouched tool %		~33-28%	7.30%	15-19%	1.50%	3-18%
P2: Core %	5.2-8.5%	~3.5%	9.20%	n<4	10.70%	3-6%
P3: Maintenance products %	1.40%		-	n=2	1.30%	3.50%
a) Width	21.4*	19.3*	18.8	17.7	18.2	20.1
b) Length	25.3***	20.9***	22.1*	19.1*	24***	20.7***
c) Weight	3.2**	2**	2.5	2.2	1.9	1.55
P4b: Blank sizes, elongated blanks (median)						
a) Width	10.7	9.01	11	10.4	11.4	10.2
b) Length	27.4	23.7	29	21.5	28	28
c) Weight	1.4	0.6	1.2	0.7	1.25	0.9
P5: Tool-to-debitage ratio	0.25-0.5	0.9-1.0	<0.1-0.2	0.3-0.5	<0.1	0.1-0.3
P6: Core sizes (median)						
a) Width	27.6	29.7	29.7	-	30.7	26
b) Length	29.6	21.9	27.5	-	28.3	25.6
c) Weight	20	11.8	22.5	-	16.5	11.7
P7: Blank-to-core ratio	2.6-3.6	~8	4-8.7	-	2.5-7	11.2-25
P8: Tool diversity	5	8	8	8	9	5
P9: Tool specialisation	+	-	+	-	+	-

observed in the previous assemblages. Cores are present in relevant quantities in non-local chert types (P2). Debitage (P4) mass is slightly smaller in non-local cherts, although with larger widths in flakes. Despite the statistically non-significant differences between local and non-local chert elongated blanks, these debitage products show the wider variability of sizes (and higher occurrence of blades) of all the assemblages. Core (P6) sizes show slightly smaller values for T6. Similarly to the Proto-Solutrean, tool-to-debitage ratios (P5) and blank-to-core ratios (P7) are slightly higher in non-local cherts. Both tool diversity (P8) and tool specialisation (P9) are higher in local cherts.

Discussion

Our findings confirm initial expectations regarding mobility patterns, raw material use, and technological strategies in southwestern Iberia during the UP. While core reduction differences between local and non-local cherts were anticipated (Table 1a-b), these differences were largely shaped by transportation strategies used to bring non-local cherts to Vale Boi. As such, the occurrence of non-local chert cores at Vale Boi depended on whether these materials arrived as finished tools or blanks—likely reflecting an individual provisioning strategy (Kuhn 2004)—or as trimmed cores and larger stone volumes, aligning with site provisioning models (Clark 1987; Kelly 1988; Roth and Dibble 1998; Kuhn 2004).

Non-local chert cores appear in all studied assemblages, though in limited numbers (e.g., in the Proto-Solutrean). While chips—often proxies for on-site knapping—were not analysed, the presence of knapping by-products, such as shatter (except in the Solutrean assemblage; see Section Datasets and analysis), and core preparation and maintenance products in non-local cherts suggests active core reduction and on-site knapping.

This seems to align with other examples from western Europe, where during the Gravettian, transportation of raw materials over 200 km was made through blocks or pre-forms. These were interpreted as an anticipated preparation for a logistical hunting, short-term occupation (Delvigne et al. 2019). A similar pattern can be seen in the Côa Valley also during the Gravettian, where non-local raw materials arrived as nodules and can be seen in the archaeological record as cores, core preparation, and maintenance products, indicating on-site knapping. However, these long-distance raw materials also show reduction sequences limited to the final stages of bladelet production and blank reuse, indicating different strategies of transportation within the same occupations (Aubry et al. 2016).

Our results indicate that non-local chert types were introduced to Vale Boi as cores or nodules, subsequently knapped on-site. The presence of knapping of these raw materials, however, does not discard the possibility of a combined strategy of core/nodule transportation, alongside blank and tool transportation within the same chert types. In fact, given the previously mentioned example of the Gravettian occupation of Côa Valley, this may present the most

parsimonious interpretation. An exception may be seen in TL cherts (TL2-6, TL9-10, TL14; Online Resource 1 Table S2), which lack associated cores and knapping debris. This absence suggests that TL cherts were introduced to the site primarily as finished tools or flakes, aligning with long-distance individual provisioning models (Kuhn 2004).

The presence of cores and evidence of on-site knapping enabled the comparison of knapping strategies—specifically, the degree of preparation and maintenance through maintenance products—as well as knapping intensity between local and non-local cherts.

Our analysis identified core preparation and maintenance products in the studied assemblages, suggesting a possible effort to preserve raw material volumes. However, these products were found in low percentages across all assemblages and chert types (<4% and $n < 7$). This indicates that, at Vale Boi, core preparation and maintenance products may not serve as reliable proxies for distinguishing between chert types. Instead, their presence may be more closely linked to specific knapping strategies and objectives, such as prioritising the production of blades and bladelets.

Core and blank size comparisons provide further insights. Non-local cherts may have undergone more intensive reduction than local cherts, as indicated by their higher blank-to-core ratios and the significantly smaller size and weight of non-local chert flakes. These results align with previous studies, which propose that the intensive reduction of cores—manifested in smaller core sizes, smaller debitage products, and a higher amount of debitage per core—may be linked to lower mobility. In this context, lower mobility results in decreased access to non-local raw materials, which are therefore more intensively reduced and eventually replaced by local raw materials (Roth and Dibble 1998; Kuhn 2004; Surovell 2009; Grove et al. 2023). However, our results show that these differences are not limited to long-term occupations and low mobility. High blank-to-core ratios and smaller flake sizes in non-local cherts are also observed in the Gravettian occupation, previously interpreted as a short-term occupation with frequent moves (Cascais et al. 2017; Belmiro et al. 2025). Due to this, we may interpret that non-local raw materials were generally more intensively reduced than local cherts throughout all the UP, independent of the duration of the occupation.

The same clear difference in size between local and non-local raw materials was not observed in elongated blanks. Albeit consistently smaller and lighter in non-local raw materials, the differences were not statistically significant. However, this may be related to a possible standardisation of elongated product production for all chert types, aiming for a production of bladelets and small blades, possibly hampered by the initial size of the raw material volumes.

Similarly to the elongated blanks, cores exhibited small, statistically non-significant, differences in size and weight between local and non-local cherts. These results may be explained by a combination of factors, including the availability of local lithic resources, transport, and knapping strategies focused on the intensive reduction and maintenance of non-local raw materials. Belmiro et al. (2023) highlight that chert nodules in the Algarve region vary between ~5–10 cm, with a maximum diameter of 20 cm. Although abundant and easily accessible in exposed cliffs, local chert nodules are generally small and prone to fracturing when extracted and normally occur fractured in secondary deposits associated with primary outcrops. As a result, the small size of local chert cores may not necessarily indicate intensive reduction but could instead reflect the initial size of available raw material volumes.

In comparison, cherts from central Portugal—the probable source of T6 cherts from Vale Boi—can be found in larger volumes (>20 cm), although smaller nodules are also present. These findings suggest that the small size of non-local chert artefacts was not necessarily constrained by raw material availability but was likely an intentional choice. This could reflect preferences for transportable nodules, strategic reduction to maximise resource utility, or a combination of both. This is further supported by the higher blank-to-core ratio observed in non-local raw materials, particularly T6. It may also explain the more frequent occurrence of heavier and larger outliers in local chert cores, compared to the relatively rare occurrence of larger outliers in non-local types (T6-7).

The intensity of reduction and maintenance discussed thus far can also be inferred from the frequency and diversity of retouched tools. In fact, retouched tools are often key elements used in the literature to distinguish between differential use of local and non-local raw materials (Bamforth 1986; Kelly 1988; Perlès 1992; Andrefsky 1994; Kuhn 2004). Our results align with expected outcomes, as non-local cherts exhibit higher frequencies of retouched tools and higher tool-to-blank ratios across all assemblages. This supports the interpretation that non-local raw materials were actively procured, and that possibly greater effort was invested in tool production (Kelly 1988; Perlès 1992; Andrefsky 1994) and the maintenance of existing artefacts through retouch (Kuhn 2004).

While the high intensity of retouch in non-local cherts aligns with expectations and hypotheses derived from other studies (Table 1 1c and 2c), their unexpectedly high tool diversity contradicts common mobility models which expect mobility to be linked with limited tool variability and an increase of easily reconfigurable tools (Odell 1981; Siegel 1984; Shott 1986). Non-local cherts at Vale Boi contain a diverse set of tool types, although less specialised tools,

such as retouched blanks, remain predominant in non-local cherts across all assemblages. Using this framework, our data suggests that these materials were not only transported as unspecialised tools but possibly as volumes that supported on-site tool production and diversification, although the transport of specialised domestic tools such as endscrapers cannot be ruled out.

The dominance of burins in the Gravettian assemblage presents a nuance to our interpretations about tool specialisation. While burins have been traditionally described as tools, other studies have focused on their role as cores for the obtention of bladelets (Sánchez-Martinez et al. 2024). In this sense, the high frequencies of burins and burin spalls may be the reflection of a particular knapping strategy, which may have been used as an easily transportable and reconfigurable raw material storage strategy, like other examples such as blade cores or bifaces (Clark 1987; Kelly 1988). However, a detailed analysis and interpretation of the burins and burin spalls is still needed to confirm this hypothesis.

While the patterns identified so far have established a distinction in the use and maintenance of local and non-local resources, it is also important to discuss the possible reasons for the varying abundance and technological patterns of non-local raw materials throughout the UP at Vale Boi, as well as the factors behind the differences observed across the different technocomplexes.

Previous studies emphasise raw material abundance and quality as key factors driving the procurement and use of non-local lithic resources over local ones, shaping their proportions, use, and maintenance. In this context, the scarcity or low quality of local resources would drive the procurement of non-local materials and require more effort in preparing transportable cores and producing tools (Kelly 1988; Perlès 1992; Andrefsky 1994). However, quality may become a less significant factor when non-local raw materials are easily accessible (Torrence 1986; Brown 1999; Akerman et al. 2002; Oestmo 2017). Even in the presence of high-quality local materials, effort was still invested in transporting non-local resources (Roth and Dibble 1998).

Regarding Vale Boi, quality does not appear to be a defining factor in raw material choice, as typologies typically associated with high-quality lithic resources are also present in other materials. For example, different types of Solutrean bifacial tools and points were previously interpreted as showing no correlation with raw materials types (Gibaja and Bicho 2013), and were produced using Lower Jurassic and Triassic local chert, which may be considered lower quality than Rio Maior Cretaceous chert (central Portugal) due to its coarser texture, less homogeneous composition, internal fractures, frequent dolomitization processes or even their smaller sizes. This suggests that the choice

of raw material was not solely dependent on quality, especially when techniques such as heat treatment—the process of heating lithic raw material to improve knapping quality (Schmidt et al. 2016)—have been identified during the Solutrean in European UP contexts (Bordes 1969; Inizan et al. 1976; Tiffagom 1998; Bachellerie and Schmidt 2022), and was also identified for the production of points during the Solutrean at Vale Boi (Gibaja and Bicho 2013).

Similarly, Vale Comprido points, the index fossil of the Proto-Solutrean, were primarily made from other lithic resources (e.g., dolerite), with only two identified points made of chalcedony and chert (Belmiro et al. 2021). This further supports the idea that raw material choice was not strictly based on quality, as these points were made from a variety of materials, including those less commonly associated with formal tools at the site.

In this case, the impact of raw material quality seems to be more related to the differences between lithological groups, which have varying textures and breakage patterns (e.g., between greywacke and chert), rather than within micro-cryptocrystalline or fibrous quartz resources like chert.

Finally, a visual inspection of a possible point cache found in the Shelter area attributed to the Gravettian revealed a high frequency of backed bladelets made from both local and non-local cherts (Bicho et al. 2016; Bicho and Cascabeira 2020). This observation further emphasises the use of diverse chert types, regardless of their quality.

Thus, non-local cherts were likely not procured solely for their quality or due to local resource limitations. Instead, their presence possibly reflects mobility strategies, territorial exploitation, and social networks that facilitated the circulation of long-distance raw materials within southwestern Iberian hunter-gatherer groups. These non-local materials were used and maintained differently, possibly due to their initial size or the need for conservation, given their more restricted or higher-cost acquisition compared to local cherts.

These mobility strategies, territorial exploitation, and social networks also help explain the distinct patterns of non-local raw material use observed between the Gravettian and other assemblages. A key distinction is the elevated proportion of non-local cherts in the Gravettian assemblage at Vale Boi, comprising approximately 50% of the total chert assemblage (Belmiro et al. 2025). When combined with technological data, this also reveals significant differences in the frequency of retouched non-local chert tools and the tool-to-blank ratio (~30% and ~1, respectively), compared to other technocomplexes (~15–19% and 0.1–0.5).

Several studies have shown that short-term occupations often rely heavily on non-local toolkits and raw materials (Torrence 1983; Surovell 2009) and are characterised by

higher reduction intensity and increased tool-to-debitage ratios (Grove et al. 2023). These differences support the interpretation of the Gravettian at Vale Boi as a set of short-term occupations (Belmiro et al. 2025).

This allows us to further expand our knowledge about chert provisioning during the UP at Vale Boi and suggest an overall interpretation for how groups were using and managing their lithic resources through time. In southwestern Iberia, the first identified UP occupations are from the Gravettian. At Vale Boi, these occupations appear to correspond to short-term settlements with frequent mobility, where non-local raw materials were transported as cores or nodules and knapped on-site. Alternatively, non-local raw materials were brought in as blanks or tools, which were consistently retouched, although individual toolkits made from limited non-local raw materials—primarily blanks or tools—were also present. Raw material volumes were intensively exploited at the site, yielding both specialised and non-specialised tools. Local raw materials were also used to produce high frequencies of retouched tools, though this was done less intensively. Given the technological differences between the Gravettian Vicentine facies and other regions such as central Portugal and southern Spain (Marreiros et al. 2015), we suggest that the approximately 250 km distance between Vale Boi and identified non-local sources reflects raw material exchanges between groups at the edges of their territories, rather than an indication of exploited territory.

These exchanges and patterns of mobility persisted throughout the UP, though with changes in the mobility and settlement patterns at Vale Boi. Over time, Vale Boi was occupied as a long-term residential site. At the beginning and during the LGM, Proto-Solutrean and later Solutrean groups, while still having access to non-local raw materials, moved less frequently, which limited the influx of these materials.

These changes in mobility frequency may be related to the increasingly harsher climatic conditions, which impacted all of Europe, while allowing regions such as southern Iberia to maintain temperate conditions where flora and faunal resources may have remained much the same (Hewitt 2000; Gómez and Lunt 2007; González-Sampériz et al. 2010; Jennings et al. 2011). The climatic stability of this ecological niche may have provided the necessary conditions for longer-term occupations of Vale Boi (Cascalheira et al. 2017), while still maintaining social interactions and contacts with other groups from Iberia seen both through technological patterns (Cascalheira 2013; Cascalheira et al. 2017; Belmiro et al. 2021) and the presence of non-local raw materials (Belmiro et al. 2025).

These non-local raw materials were still intensively exploited and maintained at the site, although hunter-gatherer groups increasingly relied on local raw materials. This

shift was likely due to the proximity of local sources, which facilitated more frequent use and discard, or even due to the introduction of new lithic treatment techniques.

Conclusion

This study demonstrates that lithic raw material procurement and technological organisation at Vale Boi were shaped by a combination of raw material accessibility, mobility strategies, and social interactions:

- Intensive reduction of non-local cherts, evidenced by higher blank-to-core ratios and increased retouch frequencies, suggests that these materials were strategically curated and maintained throughout their use-lives.
- The unexpectedly high tool diversity in non-local cherts challenges assumptions that non-local materials were only transported as finished tools. Instead, our results indicate that they functioned as versatile raw material sources, knapped on-site to meet diverse technological needs as they arose.

These findings provide new insights into hunter-gatherer mobility, social networks, and tool production strategies in southwestern Iberia. While non-local raw materials were crucial throughout the UP, their role evolved in response to changing settlement patterns and technological needs.

Future work should explore whether Vale Boi's non-local cherts were obtained through direct procurement, down-the-line exchange, or social trade networks. Additionally, applying use-wear analysis to retouched tools could help clarify whether non-local chert tools had specialised functions, further informing our understanding of raw material management and mobility strategies.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s12520-025-02339-8>.

Acknowledgements We would like to thank the Fundação para a Ciência e Tecnologia (FCT) for the funding essential for our research, and the Interdisciplinary Center for Archaeology and the Evolution of Human Behaviour (ICArEHB) for funding and providing access to the archaeological materials. We would also like to thank the reviewers for their constructive criticism and suggestions, which improved the current study and paper.

Author contributions J.B., N.F. and J.C. created the study conception and design. J.B. did the material preparation, data collection, database collection and treatment and analysis. The first draft of the manuscript was written by J. B. and N.F., X.T. and J.C. commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This study was supported by the Fundação para a Ciência e

Tecnologia (<https://www.fct.pt/>), attributed to Joana Belmiro with the contract reference 2020.08722.BD (DOI: <https://doi.org/10.54499/2020.08722.BD>). This study was also supported by the Seed Fund'21 attributed to Joana Belmiro, by ICArEHB – The interdisciplinary Center for Archaeology and Evolution of Human Behaviour, funded by the Fundação para a Ciência e Tecnologia (<https://www.fct.pt/>) under program UIDP/04211/2020. João Cascalheira is funded by the European Union (ERC-CoG-2021, FINISTERRA, 101045506). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council Executive Agency. Neither the European Union nor the granting authority can be held responsible for them. Open Access was financed by FCT – Fundação para a Ciência e a Tecnologia, within the scope of the project ICArEHB UID/04211/2025.

Data and code availability The authors confirm that all data generated and analysed during this study are available to the public in the Open Science Framework repository at: <http://www.https://doi.org/10.17605/OSF.IO/UWMPK>.

Declarations

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Akerman K, Fullagar R, van Gijn A (2002) Weapons and wunan: production, function and exchange of Kimberley points. *Australian Aboriginal Stud* 1:13–42
- Ambrose S, Lorenz K (1990) Social and ecological models for the middle stone age in Southern Africa. Edinburgh University, Edinburgh, pp 3–33
- Andrefsky W (1994) Raw-material availability and the organization of technology. *Am Antiq* 59:21–34. <https://doi.org/10.2307/3085499>
- Aubry T, Gameiro C, Mangado Llach J et al (2016) Upper palaeolithic lithic raw material sourcing in central and northern Portugal as an aid to reconstructing hunter-gatherer societies. *J Lithic Stud* 3:7–28. <https://doi.org/10.2218/jls.v3i2.1436>
- Aubry T, Barbosa AF, Gameiro C (2022) Far from flint: inferring land-use and social networks from middle and upper palaeolithic lithic assemblages (Cardina-Salto do Boi, Côa Valley, Portugal). *J Archaeol Sci Rep*. <https://doi.org/10.1016/j.jasrep.2022.103385>
- Inizan M-L, Roche H, Tixier J (1976) Avantages d'un traitement thermique pour la taille des roches siliceuses
- Bachelier J, Schmidt P (2022) Recognizing heat-treated chert: a comparison between infrared spectroscopy and fracture surface analysis. *Archaeometry* 64:39–58. <https://doi.org/10.1111/arcm.12701>
- Baker J, Solange R, Pereira D et al (2024) Evidence from personal ornaments suggest nine distinct cultural groups between 34,000 and 24,000 years ago in Europe. *Nat Hum Behav*. <https://doi.org/10.1038/s41562-023-01803-6>
- Bamforth DB (1986) Technological efficiency and tool curation. *Am Antiq* 51:38–50. <https://doi.org/10.2307/280392>
- Bamforth DB, Bleed P (1997) Technology, flaked stone technology, and risk. *Archaeol Pap Am Anthropol Assoc* 7:109–139. <https://doi.org/10.1525/ap3a.1997.7.1.109>
- Belmiro J, Bicho N, Haws J, Cascalheira J (2021) The Gravettian-Solutrean transition in Westernmost Iberia: new data from the sites of Vale Boi and Lapa do Picareiro. *Quat Int* 587–588:19–40. <https://doi.org/10.1016/j.quaint.2020.08.027>
- Belmiro J, Terradas X, Cascalheira J (2023) Creating frames of reference for Chert exploitation during the late pleistocene in southwesternmost Iberia. *PLoS ONE*. <https://doi.org/10.1371/journal.pone.0293223>
- Belmiro J, Terradas X, Dominguez-Bella S, Cascalheira J (2025) Within and beyond: chert procurement patterns during the upper palaeolithic in southwesternmost Iberia. *J Paleolithic Archaeol*. <https://doi.org/10.1007/s41982-025-00209-2>
- Bicho N, Haws J (2008) At the land's end: marine resources and the importance of fluctuations in the coastline in the prehistoric huntergatherer economy of Portugal. *Quat Sci Rev* 27:2166–2175. <https://doi.org/10.1016/j.quascirev.2008.08.011>
- Bicho N, Stiner M, Moura D, Lucena A (2007) Rockshelter studies in Southwestern Iberia: the case of Vale Boi (algarve, Southern Portugal). BAR Publishing, Oxford, pp 75–82
- Bicho N, Haws J, Almeida F (2011) Huntergatherer adaptations and the younger Dryas in central and southern Portugal. *Quat Int* 242:336–347. <https://doi.org/10.1016/j.quaint.2010.12.025>
- Bicho N, Cascalheira J, Marreiros J (2012) On the (l)edge:: the case of Vale Boi rockshelter (algarve, Southern Portugal). Oxbow Books, Oxford, pp 65–81
- Bicho N, Manne T, Marreiros J et al (2013) The ecodynamics of the first modern humans in Southwestern Iberia: the case of Vale Boi, Portugal. *Quat Int* 318:102–116. <https://doi.org/10.1016/j.quaint.2013.06.029>
- Bicho N, Cascalheira J, Gonçalves C (2017a) Early upper paleolithic colonization across Europe: time and mode of the Gravettian diffusion. *PLoS ONE*. <https://doi.org/10.1371/journal.pone.0178506>
- Bicho N, Cascalheira J, Marreiros J, Pereira T (2017b) Rapid climatic events and long term cultural change: the case of the Portuguese upper paleolithic. *Quat Int* 428:3–16. <https://doi.org/10.1016/j.quaint.2015.05.044>
- Bicho N, Cascalheira J (2020) Use of lithic assemblages for the definition of Short-Term occupations in Hunter-Gatherer prehistory. *Short-Term occupations in paleolithic archaeology*, 1st edn. Springer, pp 19–38
- Bicho N, Marreiros J, Cascalheira J et al (2016) An early Gravettian point cache from Vale Boi: Implications for the arrival of anatomically modern humans to southern Iberia. Paper presented at the 81st Annual Meeting of the Society for American Archaeology
- Binford LR, Stone NM (1985) Righteous rocks and Richard Gould: some observations on misguided debate. *Am Antiq* 50:151–153. <https://doi.org/10.2307/280641>
- Binford LR (1979) Organization and formation processes: looking at curated technologies | *Journal of Anthropological Research*: 35, 3. *J Anthropol Res* 35. <https://doi.org/10.1086/jar.35.3.3629902>
- Bordes F (1969) Traitement thermique du silex Au Solutréen. *Bulletin de la Société préhistorique française. Comptes rendus des séances mensuelles* 66:197–197. <https://doi.org/10.3406/bspf.1969.10404>
- Bradtmöller M, Pastoors A, Weninger B, Weniger G-C (2012) The repeated replacement model rapid climate change and population dynamics in late pleistocene Europe. *Quat Int* 247:38–49. <https://doi.org/10.1016/j.quaint.2010.10.015>

- Brézillon M (1968) La dénomination des objets de Pierre taillée. Matériaux pour Un vocabulaire des préhistoriens de langue française. Gallia Préhistoire 4. Centre national de la Recherche scientifique, Paris
- Brown K (1999) Raw material selection and flake production in the middle stone age of Southern africa: die Kelders cave i and Montagu cave. State University of New York at Stony Brook
- Cascalheira J (2019) Territoriality and the organization of technology during the last glacial maximum in Southwestern Europe. PLoS ONE. <https://doi.org/10.1371/journal.pone.0225828>
- Cascalheira J, Bicho N (2013) Huntergatherer ecodynamics and the impact of the Heinrich event 2 in central and southern Portugal. Quat Int 318:117–127. <https://doi.org/10.1016/j.quaint.2013.05.039>
- Cascalheira J, Bicho N, Manne T, Horta P (2017) Cross-scale adaptive behaviors during the upper paleolithic in Iberia: the example of Vale Boi (Southwestern Portugal). Quat Int 446:17–30. <https://doi.org/10.1016/j.quaint.2017.01.002>
- Cascalheira J, Alcaraz-Castaño M, Alcolea-González J et al (2021) Paleoenvironments and human adaptations during the last glacial maximum in the Iberian peninsula: A review. Quat Int 581–582:28–51. <https://doi.org/10.1016/j.quaint.2020.08.005>
- Cascalheira J (2010) Tecnologia Lítica solutrense do abrigo de Vale Boi (Vila do Bispo), 5 edn. Cadernos da UNIARQ
- Clark J (1987) In: Johnson JK, Morrow CA (eds) Politics, prismatic blades, and Mesoamerican civilization. Westview, Boulder, Colorado, pp 259–284
- Delvigne V, Fernandes P, Bindon P, et al (2019) Geo-resources and techno-cultural expressions in the south of the French Massif Central during the Upper Palaeolithic: determinism and choices. Anthropologica et Præhistorica 128/2017:39–55
- Ericson J, Earle T (eds) (1982) Contexts for prehistoric exchange. Elsevier
- Finlayson C, Giles Pacheco F, Rodríguez-Vidal J et al (2006) Late survival of Neanderthals at the southernmost extreme of Europe. Nature 443:850–853. <https://doi.org/10.1038/nature05195>
- Gamble C, Davies W, Pettitt P, Richards M (2004) Climate change and evolving human diversity in Europe during the last glacial. Philosophical Trans Royal Soc Lond Ser B Biol Sci 359:243–253. <https://doi.org/10.1098/rstb.2003.1396>
- Gamble C (1999) The palaeolithic societies of Europe. Cambridge University Press
- Gibaja JF, Bicho NF (2006) La función de Los instrumentos líticos En El Asentamiento de Vale Boi (Algarve, Portugal) estudio Del Utilitaje gravetiense y solutrense. SAGVNTVM Papeles Del Laboratorio De Arqueología De Valencia 38:9–21
- Gómez A, Lunt DH (2007) In: Weiss S, Ferrand N (eds) Refugia within refugia: patterns of phylogeographic concordance in the Iberian Peninsula. Springer Netherlands, Dordrecht, pp 155–188
- González-Sampériz P, Leroy SAG, Carrión JS et al (2010) Steppes, savannahs, forests and phytodiversity reservoirs during the Pleistocene in the Iberian Peninsula. Rev Palaeobot Palynol 162:427–457. <https://doi.org/10.1016/j.revpalbo.2010.03.009>
- Gould RA (1985) The empiricist strikes back: reply to Binford. Am Antiq 50:638–644. <https://doi.org/10.2307/280326>
- Gould RA, Koster DA, Sontz AHL (1971) The lithic assemblage of the Western Desert aborigines of Australia. Am Antiq 36:149–169. <https://doi.org/10.2307/278668>
- Gramly RM (1980) Raw materials source areas and curated tool assemblages. Am Antiq 45:823–833. <https://doi.org/10.2307/280152>
- Grove M, Hall H, Timbrell L (2023) Moving far or moving often? A neglected axis of variation in hunter-gatherer mobility. J Archaeol Sci Rep. <https://doi.org/10.1016/j.jasrep.2023.104266>
- Hewitt G (2000) The genetic legacy of the quaternary ice ages. Nature 405:907–913. <https://doi.org/10.1038/35016000>
- Horta P, Cascalheira J, Bicho N (2019) The role of lithic bipolar technology in Western Iberia's upper paleolithic: the case of Vale Boi (Southern Portugal). J Paleolithic Archaeol 2:134–159. <https://doi.org/10.1007/s41982-019-0022-5>
- Perlès C (1992) In search of lithic strategies. A cognitive approach to prehistoric chipped stone assemblages. pp 223–247
- Jennings R, Finlayson C, Fa D, Finlayson G (2011) Southern Iberia as a refuge for the last Neanderthal populations: Southern Iberia as a Neanderthal refugium. J Biogeogr 38:1873–1885. <https://doi.org/10.1111/j.1365-2699.2011.02536.x>
- Jiménez-Espejo FJ, Martínez-Ruiz F, Finlayson C et al (2007) Climate forcing and neanderthal extinction in Southern Iberia: insights from a multiproxy marine record. Quat Sci Rev 26:836–852. <https://doi.org/10.1016/j.quascirev.2006.12.013>
- Kelly R (1988) The three sides of a biface. Am Antiq. <https://doi.org/10.2307/281115>
- Kelly RL (1995) The foraging spectrum: diversity in hunter-gatherer lifeways. Percheron, Clinton Corners, New York
- Kuhn S (1991) Unpacking reduction: lithic raw material economy in the mustertian of west-central Italy. J Anthropol Archaeol 10:76–106. [https://doi.org/10.1016/0278-4165\(91\)90022-P](https://doi.org/10.1016/0278-4165(91)90022-P)
- Kuhn SL (1994) A formal approach to the design and assembly of mobile toolkits. Am Antiq 59:426–442. <https://doi.org/10.2307/282456>
- Kuhn S (2004) Upper paleolithic raw material economies at Üçağızlı cave, Turkey. J Anthropol Archaeol 23:431–448. <https://doi.org/10.1016/j.jaa.2004.09.001>
- Linscott B, Pike Alistair WG, Angelucci Diego E et al (2023) Reconstructing Middle and Upper Paleolithic human mobility in Portuguese Estremadura through laser ablation strontium isotope analysis. Proceedings of the National Academy of Sciences 120. <https://doi.org/10.1073/pnas.2204501120>
- Luedtke BE (1978) Chert sources and Trace-Element analysis. Am Antiq 43:413–423. <https://doi.org/10.2307/279398>
- Manne T (2014) Early upper paleolithic bone processing and insights into small-scale storage of fats at Vale Boi, Southern Iberia. J Archaeol Sci 43:111–123. <https://doi.org/10.1016/j.jas.2013.12.003>
- Manne T, Bicho N (2011) Prying new meaning from limpet harvesting at Vale Boi during the upper paleolithic. Trekking the shore: changing coastlines and the antiquity of coastal settlement. Springer New York, New York
- Manne T, Cascalheira J, Évora M et al (2012) Intensive subsistence practices at Vale Boi, an upper paleolithic site in Southwestern Portugal. Quat Int 264:83–99. <https://doi.org/10.1016/j.quaint.2012.02.026>
- Marreiros J, Bicho N (2013) Lithic technology variability and human ecodynamics during the early gravettian of Southern Iberian Peninsula. Quat Int 318:90–101. <https://doi.org/10.1016/j.quaint.2013.05.008>
- Marreiros J, Bicho N, Gibaja J et al (2015) Lithic technology from the gravettian of Vale boi: new insights into early upper paleolithic human behavior in Southern Iberian Peninsula. Quat Int 359–360:479–498. <https://doi.org/10.1016/j.quaint.2014.06.074>
- Marwick B (2017) Computational reproducibility in archaeological research: basic principles and a case study of their implementation. J Archaeol Method Theory 24(2):424–450. <https://doi.org/10.1007/s10816-015-9272-9>
- Marwick B, Boettiger C, Mullen L (2018) Packaging data analytical work reproducibly using r (and friends). Am Stat 72:80–88. <https://doi.org/10.1080/00031305.2017.1375986>
- McCall GS (2007) Behavioral ecological models of lithic technological change during the later middle stone age of South Africa. J Archaeol Sci 34:1738–1751. <https://doi.org/10.1016/j.jas.2006.12.015>

- Morin E (2008) Evidence for declines in human population densities during the early upper paleolithic in Western Europe. *Proc Natl Acad Sci U S A* 105:48–53. <https://doi.org/10.1073/pnas.0709372104>
- Morrow TA (1996) Bigger is better: comments on Kuhn's formal approach to mobile tool kits. *Am Antiq* 61:581–590. <https://doi.org/10.2307/281842>
- Nelson M (1991) The study of technological organization. *J Archaeol Method Theory* 3:57–100
- Odell GH (1981) The morphological express at function junction: searching for meaning in lithic tool types. *J Anthropol Res* 37:319–342
- Pereira T, Bicho N, Cascalheira J et al (2016a) Territory and abiotic resources between 33 and 15.6 ka at Vale Boi (SW Portugal). *Quat Int* 412:124–134. <https://doi.org/10.1016/j.quaint.2015.08.071>
- Pereira T, Farias A, Paixão E (2016b) Presenting lusolit: a lithotheque of knappable raw materials from central and southern Portugal. *JLS* 3:743–757. <https://doi.org/10.2218/jls.v3i2.1455>
- Gibaja JF, Bicho NF (2013) Provenience, technology, morphology and the use of proto-solutrean and solutrean points from Vale Boi (Algarve, southern portugal) : preliminary results. In: *Le Solutrén 40 ans après Smith'66. Actes du colloque de Preully-sur-Claise, 21 octobre – 1er novembre 2007. Tours : Fédération pour l'édition de la Revue archéologique du Centre de la France, 2013, pp 185–196*
- Rasilla MDL, Duarte E, Sanchis A et al (2020) Environment and subsistence strategies at La Viña rock shelter and Llonin cave (Asturias, Spain) during MIS3. *J Archaeol Sci Rep*. <https://doi.org/10.1016/j.jasrep.2020.102198>
- Riel-Salvatore J (2010) A niche construction perspective on the middle-upper paleolithic transition in Italy. *J Archaeol Method Theory* 17:323–355. <https://doi.org/10.1007/s10816-010-9093-9>
- Riel-Salvatore J, Barton CM (2004) Late pleistocene technology, economic behavior, and land-use dynamics in Southern Italy. *Am Antiq* 69:257–274. <https://doi.org/10.2307/4128419>
- Roth BJ, Dibble HL (1998) Production and transport of blanks and tools at the French middle paleolithic site of Combe-capelle Bas. *Am Antiq* 63:47–62. <https://doi.org/10.2307/2694775>
- Sanchez Goñi M, Harrison S (2010) Millennial-scale climate variability and vegetation changes during the last glacial: concepts and terminology. *Quat Sci Rev*. <https://doi.org/10.1016/j.quascirev.2009.11.014>
- Sánchez-Martínez J, Gilabert XR, Martínez-Moreno J (2024) Unraveling the burin-core dichotomy: historiographic and technological data to develop a new analytical framework for the study of on-edge artefacts. *J Lithic Stud* 11:30. <https://doi.org/10.2218/jls.7296>
- Schmidt I, Bradtmöller M, Kehl M et al (2012) Rapid climate change and variability of settlement patterns in Iberia during the late pleistocene. *Quat Int* 274:1–26. <https://doi.org/10.1016/j.quaint.2012.01.018>
- Schmidt P, Paris C, Bellot-Gurlet L (2016) The investment in time needed for heat treatment of Flint and Chert. *Archaeol Anthropol Sci* 8(4):839–848. <https://doi.org/10.1007/s12520-015-0259-y>
- Shott M (1986) Technological organization and settlement mobility: an ethnographic examination. *J Anthropol Res* 42:15–51. <https://doi.org/10.1086/jar.42.1.3630378>
- Siegel PE (1984) Functional variability within an assemblage of end-scrapers. *Lithic Technol* 13:35–51. <https://doi.org/10.1080/01977261.1984.11720849>
- Straus LG (1991) Human geography of the late upper paleolithic in Western Europe: present state of the question. *J Anthropol Res* 47:259–278. <https://doi.org/10.1086/jar.47.2.3630328>
- Straus LG (1993) Upper paleolithic hunting tactics and weapons in Western Europe. *Archaeol Pap Am Anthropol Assoc* 4:83–93. <https://doi.org/10.1525/ap3a.1993.4.1.83>
- Straus LG (1995) The upper paleolithic of Europe: an overview. *Evol Anthropol Issues News Rev* 4:4–16. <https://doi.org/10.1002/evan.1360040103>
- Surovell T (2009) Toward a behavioral ecology of lithic technology. *Cases from Paleoindian archaeology. Arizona University, Tucson*
- Tátá F, Cascalheira J, Marreiros J et al (2014) Shell bead production in the upper paleolithic of Vale Boi (SW Portugal): an experimental perspective. *J Archaeol Sci* 42:29–41. <https://doi.org/10.1016/j.jas.2013.10.029>
- Thacker P (2002) Residential mobility and lithic economizing behavior: explaining technological change in the Portuguese upper paleolithic. *Lithic Raw material economies in late glacial and early postglacial Europe. University of Michigan Press, Michigan, pp 147–160*
- Tiffagom M (1998) Témoignages d'un traitement thermique des feuilles de Laurier Dans Le Solutrén supérieur de La Grotte du Parpalló (Gandia, Espagne)/Testimonios de Un Tratamiento térmico de Las Ojas de Laurel En El solutrense superior de La Cueva Del Parpalló/Evidence for thermal treatment of Laurel leaf points in the upper solutrean of the Grotte du Parpalló. *Paleo* 10:147–161. <https://doi.org/10.3406/pal.1998.1134>
- Tixier J, Inizan M-L, Roche H (1980) Préhistoire de La Pierre taillée. *Cercle de recherches et d'études préhistoriques; Diffusion, association pour La promotion et La diffusion des connaissances archéologiques, Valbonne, [Antibes]*
- Torrence R (1983) *Time budgeting and hunter-gatherer technology. Cambridge University Press, Cambridge, pp 11–22*
- Torrence R (1986) *Production and exchange of stone tools: prehistoric Obsidian in the Aegean. Cambridge University Press, Cambridge*
- Tostevin GB (2012) *Seeing lithics: a middle-range theory for testing for cultural transmission in the pleistocene. Oxbow Books, Oxford, Oakville, CT*
- Whallon R (2006) Social networks and information: non-utilitarian mobility among hunter-gatherers. *J Anthropol Archaeol* 25:259–270. <https://doi.org/10.1016/j.jaa.2005.11.004>
- Wickham H (2015) *R packages: Organize, Test, Document, and share your code. O'Reilly Media*
- Zilhão J (2021) The late persistence of the middle palaeolithic and neandertals in Iberia: a review of the evidence for and against the Ebro frontier model. *Quat Sci Rev*. <https://doi.org/10.1016/j.quascirev.2021.107098>
- Zilhão J, Anesin D, Aubry T (2017) Precise dating of the Middle-to-Upper Paleolithic transition in Murcia (Spain) supports late Neandertal persistence in Iberia. *Heliyon*. <https://doi.org/10.1016/j.heliyon.2017.e00435>
- Zilhão J (1997) *O paleolítico superior da estremadura portuguesa, volume I*
- Belmiro J (2020) *Proto-Solutrean lithic technology of western Iberia: the sites of Vale Boi and Lapa do Picareiro. PhD thesis*
- Bicho N (1992) *Technological change in the final Upper Paleolithic of Rio Maior, Portuguese Estremadura. PhD thesis*
- Cascalheira J (2009) *Tecnologia lítica do abrigo solutrense de vale boi. PhD thesis*
- Cascalheira JMM (2013) *A INFLUÊNCIA MEDITERRÂNICA NAS REDES SOCIAIS DO SOLUTRENSE FINAL PENINSULAR. PhD thesis*
- Cascalheira J, Bicho N, Marreiros J et al (2013a) Vale Boi (Algarve, Portugal) and the solutrean in Southwestern Iberia. *Espacio Tiempo y forma Serie I. 1. Prehistoria y Arqueología*<https://doi.org/10.5944/etfi.5.2012.5376>
- Cascalheira J, Bicho N, Marreiros J et al (2013b) Vale Boi (Algarve, Portugal) and the solutrean in Southwestern Iberia. *Espacio*

- Tiempo y forma Serie I. 1. Prehistoria y Arqueología <https://doi.org/10.5944/etfi.5.2012.5376>
- Manne T (2010) Upper Paleolithic foraging decisions and early economic intensification at Vale Boi, southwestern Portugal. PhD thesis
- Mendonça C (2009) A tecnologia lítica no tardiglacial do Algarve. PhD thesis
- Oestmo S (2017) A Formal Modeling Approach to Understanding Stone Tool Raw Material Selection in the African Middle Stone Age: A Case Study from Pinnacle Point, South Africa. PhD thesis

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.