Joana Filipa Neto Belmiro

The exploitation of siliceous raw materials during the Upper Palaeolithic in the southwest of the Iberian Peninsula

A exploração de matérias-primas siliciosas durante o Paleolítico Superior no sudoeste da Península Ibérica

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Doctoral dissertation in Archaeology

Work carried out under the guidance of:

Doctor João Cascalheira

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Declaro ser o autor deste trabalho, que é original e inédito.
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I declare that I am the author of this work, which is original.
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There's a cycle here, a rhythm. Don't we need to know in advance if the next Season is going to be longer or worse somehow? How can we prepare for the future if we won't acknowledge the past?

- The stone sky, N. K. Jemisin

A small thank-you note

Foremost, a warning—I know, dramatic. Please don't expect a scientific undertone in this page but do forgive me if I slip; I have spent the last years writing—and learning to write—in the language of science, and those close to me know my waves flow long lengths and through odd currents. Just look at this last sentence.

Alright, now to the actual point; you already know what it is—after all, this is one of the first pages of a doctoral dissertation, and it does say so in the title. But while the goal of this page—here we go, that science leaking from within my fingernails. Again, you have to forgive me… this is harder, much more complex than it seems (at least for me); after all, how do you fit within a few a pages nearly half a decade of appreciation for countless of people that made the colossal task of writing a doctoral dissertation—and all that goes between the lines—a pleasant, possible, plausible undertaking?

Let's keep it simple then—thank you. All of you who shared my highs and my lows; who kept me afloat; who offered me advice, who gave me opportunities, who made me smile—all three families (blood family, friend family, work family) who helped me grow branches and sprout leaves, aiming towards the sky. And please forgive me if I choose not to name names. Hopefully, I have done a proper job of thanking everyone who took part in this journey throughout the years.

Thank you—from the bottom of my heart, *thank you*.

Let me perhaps offer here a special thank you to someone who has been my teacher and supervisor for nearly a decade now, ever since I hopped inside his office back at the faculty, asking for something to learn and analyse; someone who has taught me more than lithics and articles and R—thank you, João. You and Célia have been my rocks—pun intended.

Abstract

The Late Pleistocene was characterised by cyclical, abrupt climatic events that had significant regional environmental impacts. These environmental shifts are often associated with processes of cultural and demographic reorganisation across time and space. This project aims to investigate the economic and social adaptations of human groups during the Upper Palaeolithic (UP) in southwestern Iberia and their relationship to millennial-scale climatic events.

To this end, we analysed chert raw materials from the UP archaeological sequence at Vale Boi (Portugal). Vale Boi presents ideal conditions for a comprehensive study of raw material procurement, use, and management: it has been extensively excavated over nearly two decades using state-of-the-art methods, yet only preliminary studies of its raw materials exist. Lithic raw material exploitation, processing, and use are essential to understanding such adaptations, as raw materials are central to the technological and cultural organisation of hunter-gatherers. For this analysis, we employed a multi-method approach that combined macroscopic, petrographic, geochemical and technological analyses.

Our results indicate the consistent use of both local and non-local chert resources throughout the UP sequence. Some non-local cherts were sourced from as far as central Portugal and southern Spain, over 250 km from the site. The proportion of non-local materials was highest during the Gravettian period and decreased in subsequent occupations, which relied more heavily on local resources. We interpret this shift as reflecting changes in mobility and settlement patterns—from short-term to longer-term occupations—likely in response to the harsh climatic conditions of Heinrich Event 2 and the Last Glacial Maximum. Despite these changes, the continued presence of non-local materials suggests that long-distance social networks were maintained throughout the UP sequence at Vale Boi, revealing resilient social connections among Iberian hunter-gatherers over more than 10,000 years.

Keywords: Upper Palaeolithic; Raw Material studies; Petrography; Geochemistry

Resumo

O Pleistocénico Superior foi caracterizado pela ocorrência cíclica de eventos climáticos abruptos, que tiveram impactos ambientais significativos a nível regional. Estas alterações ambientais estão frequentemente associadas a processos de reorganização cultural e demográfica ao longo do tempo e do espaço. Este projeto tem como objetivo investigar as adaptações económicas e sociais dos grupos humanos durante o Paleolítico Superior no sudoeste da Península Ibérica e a sua relação com eventos climáticos de escala milenar. Ao analisar padrões de resiliência e inovação na aquisição e utilização de matérias-primas, em paralelo com a mobilidade dos caçadores-recolectores, este estudo investiga de que forma estes comportamentos se correlacionam com as alterações ambientais e com a evolução das dinâmicas dos territórios sociais.

A obtenção, uso e manutenção de matérias-primas líticas são aspetos fundamentais para compreender adaptações humanas, dado que constituem elementos centrais da organização tecnológica e cultural dos caçadores-recolectores. As diferenças nas proporções de matérias-primas aliadas a padrões tecnológicos permitem-nos também entender diferenças na manutenção de matérias-primas específicas e diferentes tipos de ocupação dos sítios arqueológicos. Além disso, a identificação de matérias-primas exóticas permite entender padrões de mobilidade de longa-distância e a possível participação em grupos sociais alargados.

Como tal, analisámos as matérias-primas siliciosas (sílex e calcedónia) da sequência arqueológica do Paleolítico Superior do sítio de Vale Boi (Portugal). Vale Boi apresenta condições únicas e ideais para um estudo aprofundado sobre a aquisição, utilização e manutenção de matérias-primas ao longo do Paleolítico Superior. Considerado um nicho cultural e ecológico, Vale Boi apresenta uma das sequências arqueológicas do Paleolítico Superior mais completas da Península Ibéria, e é um sítio de referência para o sudoeste ibérico onde sítios desta cronologia são escassos e se encontram mal preservados ou destruídos. O sítio conta com escavações sistemáticas há quase duas décadas com recurso a metodologias de ponta e vários estudos das coleções líticas que permitiram caracterizar a organização tecnológica, padrões de ocupação e contacto com outras regiões dos caçadores-recolectores da região. No entanto, estudos sobre as matérias-primas ainda se encontram numa fase preliminar.

De forma a alcançar os objetivos descritos acima, este estudo aborda questões relacionadas com a proveniência das matérias-primas siliciosas, padrões de mobilidade e organização tecnológica. Em particular, procuramos compreender que tipos de sílex foram explorados, como estes materiais chegaram ao sítio, e de que forma a sua gestão

esteve relacionada com estratégias de mobilidade e com mudanças tecnológicas e sociais influenciadas por variações climáticas.

Para tal, foram estudados todos os artefactos com coordenadas individuais das áreas do Terraço e Abrigo de Vale Boi da sequência do Paleolítico Superior. Esta inclui as ocupações Gravetenses (c. 32-27 ka cal BP), Proto-Solutrenses (c. 26-24 ka cal BP) e Solutrenses (c. 24-20 ka cal BP) do Terraço, e a ocupação Solutrense (c. 24-22 ka cal BP) do Abrigo.

Seguindo outros exemplos para o estudo de matérias-primas, em específico o sílex, aplicámos uma abordagem multidisciplinar. Assim, a metodologia aplicada neste estudo integra prospeções geológicas com análises macroscópicas, petrográficas, mineralógicas e geoquímicas. Desta forma, foi possível comparar o sílex geológico local e regional com o sílex arqueológico. Amostras geológicas de outras regiões foram também utilizadas de forma a entender a proveniência de sílex exótico presente no sítio. Finalmente, estudos tecnológicos dos artefactos líticos foram também integrados com os resultados da análise de matérias-primas, de forma a entender padrões de manutenção ao longo da sequência arqueológica.

Os resultados mostram o uso combinado e contínuo de recursos locais e não locais ao longo de toda a sequência do Paleolítico. Uma parte significativa do sílex utilizado em Vale Boi é de origem local, proveniente de formações de calcedónia e sílex situadas no interior, num raio de aproximadamente 10 km do sítio, ou de zonas costeiras num raio de cerca de 20 km. Estes materiais terão sido transportados para o sítio sob a forma de nódulos, provavelmente recolhidos em depósitos primários ou sub-primários.

Uma parte do sílex utilizado em Vale Boi é de origem não local. A maioria deste sílex não local parece ter sido transportada para o sítio sob a forma de nódulos, núcleos parcialmente descorticados ou volumes líticos de maior dimensão, tendo sido posteriormente talhados no local. Algumas das matérias-primas não locais foram identificadas como provenientes do centro de Portugal e do sul de Espanha, a mais de 250 km a Norte e a Este (respetivamente) do sítio. A presença de matérias-primas provenientes de longa distância em Vale Boi é interpretada como evidência de interação social entre grupos de caçadores-recolectores distintos na Península Ibérica.

Apesar dos mesmos tipos de sílex se encontrarem presentes em toda a sequência arqueológica, a proporção de sílex local e não local demonstra variações, assim como a proporção de utensílios retocados. A proporção de matérias-primas não locais e utensílios retocados é mais elevada durante as ocupações Gravetenses, diminuindo nas ocupações Proto-Solutrenses e Solutrenses, que revelam uma maior dependência de recursos locais. Esta mudança é interpretada como reflexo de alterações nos padrões de mobilidade e ocupação. Assim, a ocupação Gravetense é interpretada como uma ocupação de curta duração, possivelmente relacionada com as condições climáticas mais amenas do Evento Heinrich 3 e consequente melhoria climática. Em contraste, as ocupações subsequentes são interpretadas como ocupações de longa duração com redução da

frequência da mobilidade, possivelmente em resposta às condições climáticas adversas associadas ao Evento Heinrich 2 e ao Último Máximo Glacial e às condições climáticas mais estáveis do sudoeste de Portugal.

Apesar destas mudanças, outros padrões mantêm-se constantes ao longo da sequência arqueológica. Por exemplo, em todas as ocupações, a utilização e manutenção de sílex não local é mais intensiva, com maior redução dos núcleos e produção de utensílios retocados. Além disso, a presença contínua de matérias-primas não locais sugere a manutenção de redes sociais de longa distância ao longo de toda a sequência do Paleolítico Superior em Vale Boi, revelando uma persistência de conexões sociais entre caçadores-recolectores na Península Ibérica durante mais de 10.000 anos.

Este estudo apresenta a primeira análise abrangente das matérias-primas siliciosas associadas à tecnologia das ocupações do Paleolítico Superior no sudoeste da Península Ibérica, contribuindo para o debate contínuo sobre as adaptações humanas no passado. A investigação confirma interpretações e sugestões propostas por estudos anteriores, ao mesmo tempo que introduz resultados inovadores. Este contributo é de particular importância para o estudo do Paleolítico Superior no sudoeste ibérico, uma região pouco representada no registo arqueológico.

A criação de uma base de dados online, de acesso livre à comunidade científica, representa a primeira coleção de referência digital para o sílex da região. Esta ferramenta é fundamental para o desenvolvimento de uma produção científica acessível e transparente, oferecendo um ponto de referência valioso para estudos futuros sobre sílex em diferentes períodos pré-históricos, tanto a nível regional como em toda a Península Ibérica.

Palavras-chave: Paleolítico Superior; Estudos de matérias-primas; Petrografia; Geoquímica

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1. Introduction

This research aims to deepen our understanding of the technological, cultural, and social adaptations of hunter-gatherer groups during the Upper Palaeolithic (UP) in southwestern Europe. By examining patterns of resilience and innovation in raw material procurement and use, alongside hunter-gatherer mobility, this study investigates how these behaviours correlate with environmental changes and the evolving dynamics of social territories. The focus is on the Iberian Peninsula, particularly southwestern Iberia. Ultimately, this project will contribute to a broader understanding of how past human groups lived and adapted throughout the Upper Palaeolithic.

The UP (c. 40,000–10,000 BP) represents a key moment in human history, marked by the expansion of modern humans into Europe, significant cultural shifts, and climatic upheavals that transformed hunter-gatherer lifestyles (Bar-Yosef, 2002; Bicho et al., 2017; Gamble et al., 2004; Sanchez Goñi and Harrison, 2010; Straus, 1995, 1991). These factors have made the UP a central focus in prehistoric archaeology, particularly regarding human adaptations and cultural transitions.

The Iberian Peninsula has played a critical role in this research. Its cultural and geographical specificities offer valuable opportunities to study cultural continuity and disruption through time within a single site or region.

The impact of climate on human culture, resilience, and mobility is one of the key research topics of the UP in Iberia (e.g., Bicho et al., 2017; Bicho and Haws, 2012; Bradtmöller et al., 2012; Cascalheira and Bicho, 2013; Morin, 2008; Schmidt et al., 2012; Straus, 1991). Patterns of change and adaptation have been identified primarily through lithic technological analyses, leading to the definition of the major technocomplexes that characterise the UP in Iberia: Aurignacian, Gravettian, Proto-Solutrean, Solutrean, and Magdalenian. These technocomplexes exhibit distinct knapping strategies, technological patterns, and raw material use, reflecting the technological reorganisation of past human groups. Additionally, changes in territory expansion, mobility, and social networks can be

observed through variations in technological choices and the presence of long-distance raw materials (Bar-Yosef, 2002; Fullola Pericot, 1979; Schmidt et al., 2012; Straus, 1991; Zilhão, 1997).

The Iberian Peninsula has often been described as a refugium during the coldest periods of the Late Pleistocene (Bicho et al., 2017; Consuegra et al., 2002; Gómez and Lunt, 2007; González-Sampériz et al., 2010; Hewitt, 2000; Jochim, 1987; Jones, 2013), providing milder conditions than northern Europe and supporting stable human occupation throughout the UP. However, during abrupt climatic events such as Heinrich Events and the Last Glacial Maximum, the region experienced colder temperatures, reduced precipitation, and vegetation shifts. Even within Iberia, north/south differences have been identified: during abrupt climatic events, arboreal taxa such as oak were replaced by infertile heathlands in northern Iberia or semi-desert steppe vegetation in southern Iberia (Boessenkool et al., 2001; Fletcher et al., 2010; Fletcher and Sanchez Goñi, 2008; Naughton et al., 2009, 2007; Roucoux et al., 2001; Roucoux et al., 2005; Sánchez Goñi et al., 2000; Sánchez Goñi et al., 2008; Turon et al., 2003; Zapata et al., 2003). This would have resulted in the expansion of dry, risk-prone environments. Instead of being uniformly hospitable, Iberia may have exhibited a "leopard coat" distribution of ecological niches (Jennings et al., 2011; Schmidt et al., 2012). These niches likely supported continuous human occupation, leading to the formation of multicomponent sites and eco-cultural niches (Banks et al., 2008; Cascalheira et al., 2017b; Cascalheira and Bicho, 2013; Fortea Pérez and Jordá Cerda, 1975; Haws, 2012; Yravedra et al., 2016).

Some studies suggest a chronological correlation between climatic shifts and the emergence of major technocomplexes, implying that cultural reorganisation may have been triggered by environmental changes that altered landscapes and essential resources (e.g., Bicho et al., 2017; Bradtmöller et al., 2012; Cascalheira and Bicho, 2013). These studies also indicate shifts in territory expansion/contraction, settlement types, mobility, and intergroup contacts (Schmidt et al., 2012). While cultural changes are not necessarily deterministic responses to climate fluctuations, it is evident that hunter-gatherers adapted to their landscapes. Cultural, technological, and social transformations provide key insights into how and why human groups adapted at different times.

The study of raw materials, alongside lithic technological analyses, is a powerful tool for identifying patterns of change and adaptation, particularly in landscape use and

mobility. Raw materials found at archaeological sites reflect human decision-making and technological organisation (Bamforth and Bleed, 1997). These patterns provide crucial insights into how hunter-gatherers interacted with their environments and adapted to shifting conditions (Féblot-Augustins, 1993; Kuhn, 1995; Mellars, 1996). Variability in raw material use at a given site may result from factors such as mobility and procurement strategies influenced by climate (Ambrose and Lorenz, 1990; Binford and Stone, 1985; Gould and Saggers, 1985; Kuhn, 2004, 1991; McCall, 2007), settlement patterns (Grove et al., 2023; Kuhn, 2004; Surovell, 2009), or exchange networks and social interactions (Akerman et al., 2002; Torrence, 1986; Whallon, 2006; Wurz, 1999).

The study of raw materials from UP sites in Iberia, particularly chert—a key raw material widely used for tool production—has provided valuable insights into hunter-gatherer procurement strategies, mobility patterns, and social networks.

A clear example is the identification of long-distance contacts between regions in Iberia, suggesting complex mobility and procurement patterns throughout the UP (e.g., Corchón Rodríguez et al., 2016; Lombera-Hermida et al., 2016; Ortega, 2003; Sánchez de la Torre et al., 2023; Tarriño et al., 2015). The Côa Valley sites in northeastern Portugal are a particularly emblematic case, as non-local chert is present throughout the UP sequence, with potential sources located 150–250 km away in both southwestern (central Portugal) and southeastern (central Spain) directions. These patterns have been interpreted as evidence of exchange networks facilitated by seasonal movements and social interactions between groups across Iberia (Aubry et al., 2022, 2004).

Compared to other Iberian regions, where raw material studies are more common, knowledge of UP hunter-gatherer lifeways, organisation, and social networks in southwestern Iberia has primarily been derived from lithic technology and faunal analyses. Much of this research has focused on Vale Boi, the only well-preserved UP site in the region. This presents a unique opportunity to investigate hunter-gatherer adaptations in a key area of human occupation during this period.

Vale Boi, located in southwestern Iberia, is a multi-component site spanning several UP technocomplexes, from the Gravettian (c. 32 ka cal BP) to the Magdalenian (c. 15 ka cal BP) (Bicho et al., 2013; Bicho et al., 2012, 2007; Cascalheira et al., 2017b; Cascalheira and Bicho, 2013; Manne et al., 2012; Manne and Bicho, 2011). The site,

considered an eco-cultural niche, provided stable climatic conditions even during colder periods, supporting continuous residential occupations that have been consistently dated (Belmiro et al., 2021; Bicho et al., 2013; Cascalheira et al., 2017b) and studied. Apart from the paleoenvironmental studies referred to above, a single identified charcoal fragment recovered from Vale Boi, belonging to the species *Arbutus Unedo* (strawberry tree) and dated to c. 32 ka cal BP, suggests a Mediterranean-like forest environment in the region, at least during the Gravettian occupation (Bicho et al., 2013).

Well-preserved faunal assemblages at Vale Boi, including terrestrial and marine components, have also been key to further ascertaining the stable conditions and residential character of the occupations throughout the UP. Archaeofaunal studies have identified several hunted animal species, dominated by rabbit, red deer and horse. The analysis of deer and horse bones suggested a marked seasonal hunting pattern, with the site being most likely occupied during spring or early summer. Other terrestrial species have also been found in lower quantities at the site and interpreted as the result of hunting activities, such as European ass, aurochs, ibex, wild boar and even carnivores and medium/large sized birds (Manne et al., 2021).

Despite being composed of a small assemblage, the study of the marine resources revealed an important element of subsistence at Vale Boi. The marine assemblages are composed of shellfish, gooseneck barnacles, a fish vertebra and a small cetacean vertebra (although the latter cannot be ascribed to human economic activities) (Manne and Bicho, 2011). The shellfish component is dominated by limpets and was associated with rocky coast environments, despite other shellfish species also indicating the exploitation of sandy and muddy environments (Manne et al., 2012; Manne and Bicho, 2011).

Extensive lithic assemblages from the UP sequence of Vale Boi have also undergone technological analysis, revealing patterns of technological change and resilience (Belmiro et al., 2021; Cascalheira et al., 2013; Gibaja Bao and Ferreira Bicho, 2013; Horta et al., 2019; Marreiros et al., 2015). Based on some of these studies, the site has also been identified as a centre for knowledge transfer, particularly during the Last Glacial Maximum (Cascalheira, 2019; Cascalheira, 2013).

Despite extensive technological studies of Vale Boi's lithic assemblages, macroscopic, microscopic, and geochemical analyses of chert remain limited (Pereira et

al., 2016a; Verissimo, 2004). This gap hinders research into raw material procurement and use, mobility, and connections between southwestern Iberia and other regions.

Consequently, Vale Boi presents an exceptional opportunity to advance understanding of UP hunter-gatherer adaptations, mobility, and technological and social organisation in Iberia.

Focusing on the lithic assemblages from Vale Boi, this research aims to investigate chert procurement, use, and mobility patterns throughout the UP of southwestern Iberia, as well as their relationship with the techno-cultural dynamics of each technocomplex and climatic changes.

To achieve this, we address the following research questions:

- What types of chert were exploited by hunter-gatherer groups in southwestern Portugal, and how were these materials introduced to the site?
- How frequently did these groups move across the landscape, and can long-distance movements or social contacts be identified through the presence of non-local cherts?
- How were different chert types managed by hunter-gatherer groups, and what impact did mobility have on their technological organisation?
- How did technological and social organisation evolve over approximately 10,000 years of the UP in southwestern Portugal, and how might climatic changes have influenced these adaptations?

To address these questions, this research employs a multi-method approach, integrating geological surveys with macroscopic, petrographic, mineralogical, and geochemical analyses, alongside technological studies of chert lithic artefacts.

The research includes three main papers and a chapter, each focusing on a specific topic necessary to answer our research questions. As a result, this dissertation is structured as follows:

- Chapter 2, titled “Creating frames of reference for chert exploitation during the Late Pleistocene in southwesternmost Iberia” (Belmiro et al., 2023), offers a

geological characterisation of chert sources in the Algarve region, employing macroscopic and petrographic (thin section microscopic analysis) methods. The paper presents a reference collection and database of local and regional chert resources, which is crucial for distinguishing between local and non-local cherts when analysing an archaeological assemblage.

- Chapter 3, titled "Within and beyond: chert procurement patterns during the Upper Palaeolithic in southwesternmost Iberia" (Belmiro et al., 2025), focuses on the analysis of chert artefacts from the UP sequence at the archaeological site of Vale Boi, using both macroscopic and petrographic (thin section microscopic analysis) methods. These artefacts are compared with geological reference collections. The paper offers new insights into the presence of local and non-local cherts across the various UP occupations, identifies the probable sources of non-local cherts, and explores changes in the distribution of chert types over time.

- Chapter 4, titled "Within chert: a multi-technique mineral and geochemical approach to the study of chert in southwestern Iberia", builds on the previous chapters by applying various techniques to analyse geological and archaeological chert samples. The chapter provides data on the mineral and chemical composition of cherts through X-Ray Diffraction (XRD), Scanning Electron Microscopy and Energy Dispersive X-Ray Spectroscopy (SEM-EDS), and portable X-Ray Fluorescence (pXRF). These methods allow for a more comprehensive and holistic approach to the samples and enable the use of chemical composition to refine the source attributions of archaeological cherts.

- Chapter 5, titled "From stone to tool: how raw materials influenced Upper Palaeolithic technology at Vale Boi, southwestern Iberia" (submitted), combines the previously obtained data on chert types (particularly regarding the distinction between local and non-local cherts) with technological data. The paper explores various patterns of chert use and management.

- Chapter 6 synthesises the results and contributions of the previous chapters and discusses the broader implications of these patterns for understanding human behaviour.

- Chapter 7 presents a small conclusion, discusses the remaining gaps and opens avenues for future research.

- Appendix A includes the repository links and lists of supplementary materials belonging to the articles and chapter.

Together, these papers and chapters present the first comprehensive study of chert raw materials associated with technology from UP occupations in southwestern Iberia and contribute to the ongoing discussion on past human adaptations.

The creation of an online database freely accessible to the scientific community provides the first online reference collection for cherts in the region. This is crucial for the development of accessible and transparent scientific production, as it offers a valuable point of reference for future studies on chert across various prehistoric periods, not only in the region but also throughout the Iberian Peninsula.

2. Creating frames of reference for chert exploitation during the Late Pleistocene in southwesternmost Iberia

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Abstract

Southwestern Iberia has played a key role in characterizing Late Pleistocene human ecodynamics. Among other aspects of human behaviour, chert procurement and management studies in this region have received increasing attention in the past two decades, especially focusing on the sites showing repeated human occupation, such as the case of Vale Boi (Southern Portugal). However, these studies have been very limited in their geographical scope, and mostly focused on brief macroscopic descriptions of the raw materials. To further our knowledge of the relationship between regional availability of raw materials and its impact on human adaptations and mobility, a more detailed approach to characterising geological sources is needed. This paper characterises chert raw materials location, diversity, and availability in a geologically well-defined region of southern Portugal—the Algarve. Through macroscopic and petrographic approaches, we provide a detailed characterisation of geological chert sources to build a frame of reference for chert exploitation in the region. Our results show that there are four main chert formations in Algarve, and that despite the within-source variability, sufficient

differences at macroscopic and petrographic levels are present to allow clear source attribution. These results provide a baseline for raw material studies in archaeological assemblages across southwestern Iberia, that will be essential to further characterize the dynamics of human behavior in some of the most important eco-cultural niches.

Keywords: Chert raw material; Petrography; Southern Portugal; Provenance studies

2.1 Introduction

Southern and Western Iberia have often been considered key areas to understanding techno-cultural transitions from the Middle Palaeolithic to the end of the Upper Palaeolithic. As territories located at the western tip of the European continent and with a generally stable climate even during the coldest periods punctuating the Late Pleistocene, these have been regarded as some of the most significant glacial refugia in Europe (Carvalho et al., 2022; Gómez and Lunt, 2007; González-Sampériz et al., 2010; Hewitt, 2000). For this reason, Southwestern Iberia has frequently been at the centre of some of the most debated topics regarding Late Pleistocene human adaptations (Cascalheira et al., 2017b; Finlayson et al., 2006; Zilhão et al., 2017). A particularly good example is the region's role in possibly being one of the last territories to be occupied by Neanderthal populations right before their complete disappearance (Finlayson et al., 2006; Zilhão et al., 2017).

Neanderthals occupied the European continent for more than 300.000 years and are thought to have disappeared while modern humans arrived on the territory (Finlayson et al., 2006; Jennings et al., 2011; Mellars, 2004; Rogers et al., 2017; Trinkaus and Howells, 1979). The last territory where Neanderthal populations seemed to exist was southern Iberia, around c. 37 thousand years ago (Zilhão et al., 2017), or perhaps even earlier (Carvalho et al., 2022; Finlayson et al., 2006; Tzedakis et al., 2007). This region is key to understanding how Neanderthals survived until such a later chronology, the degree and types of interaction those populations may have had with modern humans (Finlayson et al., 2006; Zilhão et al., 2017), and how and why they eventually went extinct (Dalen et al., 2012; Melchionna et al., 2018).

Another example is southwestern Iberia's importance in the discussion of Upper Palaeolithic technocomplexes transitions. Previous studies have discussed the territory's

potential as a refugium during cold and harsh climatic conditions (Gómez and Lunt, 2007; Jennings et al., 2011; Rodríguez-Sánchez et al., 2010). The Heinrich Event 2 (HE 2) at the onset of the Last Glacial Maximum (LGM), for example, is a period marked by important social and technological transformations. This climatic event was characterised by abrupt and drastic climatic changes that impacted human behaviour all across westernmost Europe (Gamble et al., 2004; Sanchez Goñi and Harrison, 2010). The identification of a Proto-Solutrean phase in central and southern Portugal with a very distinct index fossil (the Vale Comprido point), and its direct association with the HE 2 (Cascalheira and Bicho, 2013), put these regions amongst some of the most important case studies of how environmental dynamics have affected human adaptations during the last glacial.

Other studies have expanded upon this notion of climatic refugia during harsh climatic events to understand the Iberian Peninsula as a long-term eco-cultural refugia (Cascalheira et al., 2017b). Using this framework, this territory would consist of several ecological niches, consistently used through time, possibly due to the stability in the richness and variety of resources. This continuous use would then create long-term regional adaptive structures, which, when correlated with the ecological niches, Cascalheira et al. (2017b) have referred to as eco-cultural niches. In fact, it seems that a large number of caves and rock shelters in Iberia are multi-layered, giving validity to the aforementioned framework (Schmidt et al., 2012). These eco-cultural niches provide an exceptional opportunity to understand long-term dynamics regarding biotic and abiotic resource exploitation since they can provide details on how human populations maintained or changed their adaptive systems when facing environmental changes, and cultural and social transformations or constraints.

One of such possible Late Pleistocene eco-cultural niches to which this theoretical framework has been previously applied is the archaeological site of Vale Boi. This multi-component site is located in westernmost southern Iberia, in a region currently known as the Algarve, and comprises one of the most complete Upper Palaeolithic chronocultural sequences of southern Iberia (Bicho et al., 2013; Cascalheira et al., 2017b; Cascalheira and Bicho, 2013).

Several cross-scale complex interactions have been identified, displaying resilient behaviours throughout the Upper Palaeolithic maintained by their eco-cultural niche, but also adaptation behaviours motivated by niche diversity, social networks, and climatic

changes (Cascalheira et al., 2017b). Some of these resilient elements are, for example, the continuous use of strategies like grease rendering and selective hunting patterns, site function, certain lithic technology patterns, and the functional specialisation of lithic raw materials. The maintenance of social networks through the identification of possible long-distance lithic raw materials has also been suggested (Pereira et al., 2016a). The identification of these patterns has been reliant on the great amount of studies that have originated from the archaeological site of Vale Boi (Bicho et al., 2017; Bicho and Haws, 2012; Manne et al., 2012; e.g., Pereira et al., 2016a).

A large portion of these studies has focused on lithic technology (Belmiro, 2020; Cascalheira, 2010; Marreiros et al., 2015), and unlike other regions of Portugal (Aubry et al., 2022, 2004; Aubry and Igreja, 2009; Costa et al., 2022; Jordão and Pimentel, 2022; Pereira et al., 2022, 2021), archaeological studies focusing on raw materials, and especially chert, have been more scarce, focusing mostly on brief macroscopic results or the differentiation between possibly local and non-local sorts of raw materials. Despite the scarcity of these studies, chert played a significant role in early and later prehistory at Vale Boi (Belmiro, 2020; Cascalheira, 2010; Marreiros, 2009) and across most of Prehistory in southern Portugal (Bicho et al., 2003; Zambujo, 1998). As an essential part of Late Pleistocene hunter-gatherer adaptations, lithic raw materials have the potential to provide insights into the adaptive strategies of those populations (Féblot-Augustins, 1993; Kuhn, 1995; Mellars, 1996), mostly regarding land-use, technological organisation, but also cultural and social interactions. In fact, the selection and procurement of raw material has been suggested as a key stage for the technological organisation of hunter-gatherer groups (Bamforth and Bleed, 1997). Thus, changes in the frequencies of raw materials within the archaeological records may provide evidence for changes in that organisation, or even resilience of specific choices, all of which can reflect culturally transmitted preferences within a group of hunter-gatherers (Brown, 1999). Several models, both formal and informal, have shown that changes of raw material in the archaeological record may reflect different procurement strategies (Binford, 1979; Binford and Stone, 1985; Gould, 1985; Gould and Saggers, 1985), either related to mobility strategies (Ambrose and Lorenz, 1990; Kuhn, 2004, 1991; McCall, 2007) or changes in the availability of raw materials, possibly related to environmental change (Brantingham, 2003; Brown, 1999). Raw materials are also closely linked to the tools

produced with them—the costs of manufacturing technology can be related to the availability of raw materials in the landscape (Bousman, 1993; Mackay and Marwick, 2011; Parry and Kelly, 1987; Torrence, 1983), or the characteristics of the raw materials which might relate to functionality (Mackay, 2008; Minichillo, 2006; Stout, 2002), through the choice of raw materials for specific technologies (Brown, 1999). Furthermore, changes in the raw materials can also be related to the establishment of social networks (Whallon, 2006) and the horizontal transmission of preferences through trade (Brown, 1999).

In order to explore the aforementioned theories and models in an archaeological site, especially when trying to understand land-use and the adaptive strategies of an eco-cultural niche like what is proposed for southwesternmost Iberia, it is necessary to know the landscape and the raw material sources available in the territory. To distinguish between local and non-local raw materials, first, it is necessary to understand the characteristics of the local sources and establish a comparative database that can be used for the analysis of an assemblage. This is true for most of the informal models which try to understand why raw materials change in the archaeological record. Formal models focusing on raw material use posit that it is necessary to have detailed sourcing data in order to adequately apply the models to a region or an archaeological assemblage (Pop, 2015; Surovell, 2009). In fact, the creation of such a database is a starting point for most raw material-focused studies, independent of the geography or studied chronology (Bustillo et al., 2009; Driscoll et al., 2016; Ekshtain and Zaidner, 2022; Luedtke, 1992). In western Europe, there have been substantial efforts in creating comprehensive knowledge about chert-bearing formations, which resulted in important lithotheques and databases (Fernandes et al., 2013; Ortega and Terradas, 2014; Sánchez et al., 2014), and multidisciplinary studies of raw material use throughout prehistory (Aubry et al., 2022; Delagnes et al., 2006; P. Fernandes et al., 2012; Rodríguez et al., 2011; Terradas and Ortega, 2017; Turq et al., 2017), as early as the 1980s.

In southern Portugal, previous efforts have been made to create such a database. The work of Verissimo (2004), albeit focusing on the occurrence of chert solely in western Algarve, provided the initial basis for comparative studies with the assemblages from some Late Pleistocene sites based on macroscopic approaches. The creation of LusoLit, a lithotheque currently hosted at the University of Algarve (Pereira et al., 2016b), and the

collection of samples from several outcrops in the region provided a new leap in the study of chert in the region. A few geological studies have also contributed to understanding the availability and characteristics of chert in southern Portugal (Ribeiro, 2005; Rocha, 1976). Nevertheless, these studies are often unpublished or provide answers to geological questions, which hamper the comparative use of the data with archaeological assemblages. A large portion of chert-bearing outcrops in southern Portugal remains unstudied, both by archaeologists and geologists. As such, further analyses of the overall variability, location, and availability of chert nodules in the Algarve are necessary to start testing behavioural models of land-use and abiotic resource exploitation.

Given the potential for an in-depth raw material study at a possible Late Pleistocene eco-cultural niche such as Vale Boi—also due to the ubiquitous presence of chert throughout the stratigraphy, as one of the main raw materials used for lithic technology in the site (Belmiro, 2020; Cascalheira, 2010; Marreiros, 2009)—in this study we explore the location, diversity, and availability of chert raw materials in the southernmost region of Portugal, the Algarve. Our main goal is to establish a reference for chert raw materials in an understudied region in regards to lithic materials, that can be used for future studies addressing chert exploitation in the Algarve and elsewhere. This includes the development of a methodological approach adapted to the study area, by testing the potential of macroscopic and petrographic approaches for the characterisation of regional cherts. The data presented here is also fully integrated into an online lithotheque (LusoLit) that is now freely available and can be built upon and improved as new data becomes available.

2.2 Geological setting and chert groups

2.2.1 Geological setting

The Algarve is the southernmost region of Portugal, framed north by the Alentejo region and east by Spain. To the west and south, it is bordered by the Atlantic Ocean. It extends for ~130 km E-W and ~50 km N-S and is characterised by a variety of geomorphic sub-regions and geological units, which make this region a complex territory (Figure 2.1). On the north sector of the Algarve, the Serra Algarvia is characterised by a mountainous range with a dense hydrographic network, which separates the Algarve from Alentejo. On the south sector, the Litoral is characterised by a flatter, long strip of land, that extends through all of the coastal strip of the Algarve. The Barrocal is nested between the other sub-regions and has a more moderate relief, characterised by carbonated Jurassic formations and important subterranean water circulation (Gago, 2007).

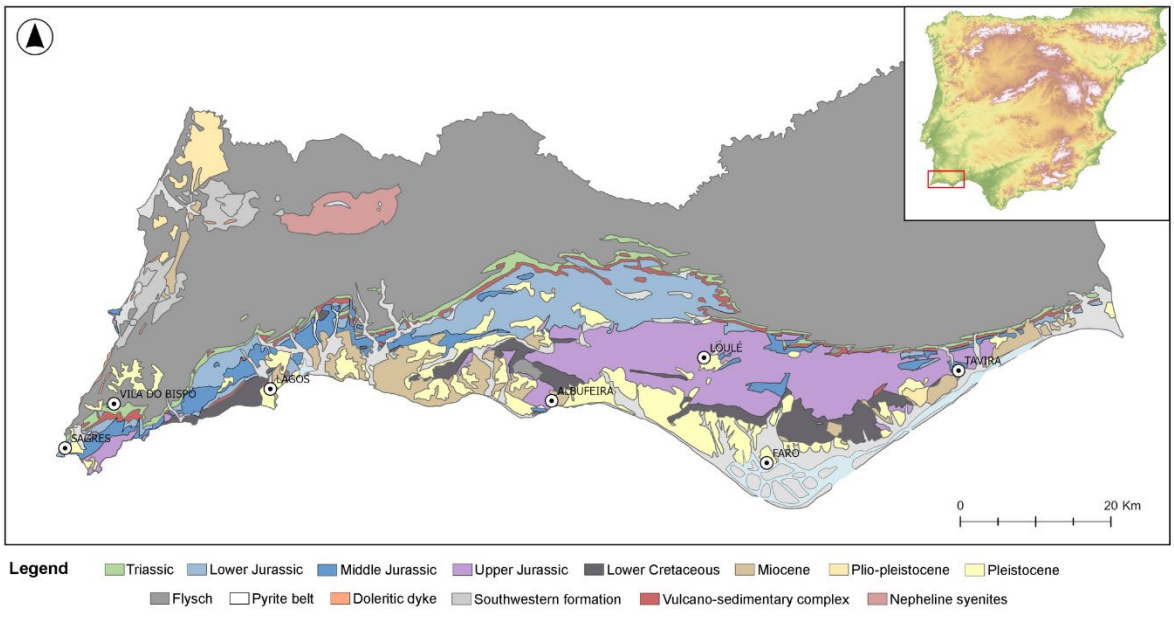

Figure 2.1. Geological map of the Algarve region. The map represents the several geological layers and formations, as well geomorphic sub-regions. The geological data was obtained through the vectorisation of the geological raster maps (Carta Geológica de Portugal, 1:500 000 scale) made available by LNEG (Laboratório Nacional de Energia e Geologia).

Geologically, the Algarve is composed of two main geological units: the South Portuguese Zone (SPZ) and the Algarve basin. The SPZ is located in the north sector of the Algarve, extending up to Alentejo (Paulo Fernandes et al., 2012). Its main lithologies are schist, greywacke and quartzite (Paulo Fernandes et al., 2012; Pereira et al., 2016a). The SPZ is overlain unconformably by the Mesozoic sedimentary rocks of the Algarve basin (Paulo Fernandes et al., 2012). The basin corresponds to the Mesozoic-Cenozoic sediments that outcrop south of the Algarve, from the westernmost to the easternmost point of the region, and it is associated with the opening of the central Atlantic Ocean and with the eventual oceanic crust formation in the western part of the Tethys sea, between the Algarve and North Africa (Terrinha et al., 2006). Mesozoic sedimentation of the basin started in the Triassic and continued thereafter. In the Lower Jurassic (Lower Pliensbachian, also regionally known as Carixian), the basin was divided into two sub-basins—western and eastern sub-basins (Rocha, 1976; Terrinha et al., 2006).

The existence of the two sub-basins and the expansion and retraction of the sea created a variety of sedimentation environments, such as external and internal platforms, continental, hemipelagic and deep marine (Terrinha et al., 2006), as well as moments of sedimentation hiatus. This variability in deposition environments created a variety of sedimentary facies, with moments of more or less homogeneity throughout this period. For example, during the Lower Pliensbachian, in the Lower Jurassic, the sediments in the western sub-basin can be described as marine of external platform, while the sediments of the eastern sub-basin can be described as marine of internal platform. During the Upper Jurassic however, the basin is marked by a moment of prominent lithofacies variation, followed by a moment of uniformity in both sub-basins (Terrinha et al., 2006). Understanding the Algarve basin is key for raw material studies in the Algarve, especially when studying chert, since it is in the basin, more specifically in the Jurassic sediments, where chert primarily outcrops in the region.

2.2.2 Chert outcrops

Within the Algarve area, the presence of chert may be associated with carbonates in limestone and dolomite formations. This is explained by characteristics (such as the presence of water or specific temperatures and pH) that are ideal for both the formation

of limestone and the precipitation of silica (Luedtke, 1992). The pelagic and marine environments of the Algarve basin during the Jurassic gathered those such ideal characteristics: as shown by Ribeiro (2005), the cherts from the Lower Jurassic are the result of early diagenic silicification of carbonate sediments. The existence of two basins with different sedimentation environments also shows potential for the existence of different types of chert throughout the basin and their differentiation. For example, during sedimentation, skeletal grains of fossils may be preserved. Many of these fossils are restricted to specific environments and time intervals (Flügel, 2010), which may allow the identification of chert outcrops through the fossil content. The basin and sub-basins thus show potential for the existence of different geological formations with different chert types and their study.

Previous works, both geological and archaeological, confirm that chert is present in the Algarve in the Jurassic limestone or dolomitic limestone layers of the Algarve basin. This means that chert outcrops can be identified in the central/south sector of the region, from west to east. Variability in chert availability, as well as chert types, is expected, considering that during the sedimentation process, the Algarve basin was already subdivided and in constant environmental change. Due to this, several formations with chert nodules can be identified in the Algarve, attributed to different sub-periods of the Jurassic.

In the western sector of the Algarve, chert can be found in the Lower Jurassic (Carixian) formations, in limestone or dolomitic limestone layers (Rocha et al., 1979; Rocha, 1976), often visible in areas where the layers are exposed, such as beach-generated cliffs and associated deposits, like Cabo de S. Vicente (CSV) and Praia do Belixe (PBX). These formations with chert nodules are also visible inland, albeit more scarcely, as is the case of the small outcrop named Ferrel (FER), 3 km from the current coastline. Lower Jurassic chert-bearing formations are barely existent in the centre/east sector of the Algarve, with one single formation with micro-nodules identified in geological works (Oliveira, 1992).

Middle Jurassic geological layers with chert nodules are only found in the centre/east sector of the Algarve in a geological formation called the Malhão formation. The formation can be described as carbonated, from a marine sedimentation environment. Chert in this formation has been identified in two distinct layers:

conglomerates with micritic limestone intercalations with chert beds and nodules, characterised by the presence of sponge spicules and radiolarians (Manuppella et al., 1987); microcrystalline limestones with chert nodules characterised by the presence of silicified malacofauna and silicified corals (Manuppella et al., 2007).

Finally, Upper Jurassic sediments with chert nodules have also been mostly identified in the centre/east sector of the Algarve, attributed to the Jordana formation. This formation is characterised by dark-grey limestones, with frequent secondary silicifications with abundant fossil fragments (Manuppella et al., 2007; Manuppella et al., 1987; Rocha et al., 1989). Upper Jurassic sediments with chert nodules in western Algarve (Kimmeridgian formations) have only been identified in one area, between Ponta da Atalia (PtA) and Praia da Mareta (MAR) (Rocha et al., 1979). Given the differences of the cherts and formations between the western and eastern sectors of the Algarve already established in previous works, this division will be followed in the present study.

2.3 Materials and methods

To locate and characterise chert formations and corresponding outcrops in southern Portugal and understand the chert's characteristics, a macroscopic and petrographic approach was applied to the study of geological samples which were collected through fieldwork. Combining different analyses and methods provides a comprehensive approach to reconstructing the geological and geographical origin of raw materials, especially since different methods have their inherent limitations (Luedtke, 1992). Several other similar methodologies and approaches have been applied in other regions (García-Simón and Domingo, 2016; Gómez de Soler et al., 2020; Terradas and Ortega, 2017; Tomasso et al., 2019).

However, the chosen analysis techniques should be adapted to the specific geographic context, the research questions, the problematics, and the characteristics of the types of cherts in question (Luedtke, 1992). Since only preliminary studies of raw materials were applied in the western portion of southern Portugal, and petrographic data have been shown to provide good results for the characterisation of cherts in this region (Ribeiro, 2005), the two methodologies were chosen for the study. The geological

samples used in this study were obtained during fieldwork, between August 2021 and June 2022. The prospected locations were chosen after reviewing previously known research, which included preliminary raw materials studies in the region (Pereira et al., 2016a; Verissimo, 2004), geological scientific papers and theses focusing on the Algarve basin and concerning chert-bearing formations and lithologies (Marques, 1983; Ramalho, 1985; Ribeiro, 2005; Rocha, 1976), and geological maps, which signalled the presence of chert nodules within the formations and geological layers (Manuppella et al., 2007; Manuppella et al., 1987; Oliveira, 1992, 1984; Rocha et al., 1989; Rocha et al., 1983; Rocha et al., 1979). Unpublished data and coordinates for unsurveyed locations with potential for chert-bearing outcrops gathered during the organisation of the LusoLit lithotheque were also checked. Whenever coordinates or specific locations for known outcrops were available, these were directly visited, and the surrounding area was surveyed to understand the extension of the outcrops and to locate possible secondary deposition outcrops nearby. When no specific locations within a formation were described (for example, in geological maps) several areas with more potential to find chert outcrops within one formation were surveyed. Samples were collected whenever possible, focusing on both primary and secondary outcrops. When chert nodules within one single outcrop showed macroscopic differences (such as differences in colour, texture, translucency, or cortex), samples of each different nodule were collected, to cover all chert variability within the outcrop, and understand chert variability within the formation. This variability was also recorded using a database (to distinguish between homogeneous or heterogeneous chert nodules within the outcrop) and through photography (Figure 2.2). All samples were registered with resource to a free android app (Archaeosurvey) which was designed for archaeological surveys, and records site location and characteristics (Cascalheira et al., 2017a), further adapted for raw material source surveys (Abrunhosa et al., 2017). The version of the software used for fieldwork is an adaptation of the latter apps and records data related to outcrop characteristics and conditions (e.g., abundance, visibility, access, geomorphology, chert morphology, and conditions). All data related to the app and fieldwork can be found in the Supplementary Online Materials (S1 Table). Individual IDs were associated with each sample, which includes sequential numbers (based on recovery order, e.g., SP10) and outcrop code (e.g., PdA).

A two-step approach was applied to characterise the geological samples. These include 59 geological samples (Table S2), currently located at ICArEHB's laboratories (University of Algarve). No permits were required for the described study, which complied with all relevant regulations. The samples were analysed macroscopically following a pre-established dataset. The variables were defined based on specialised literature (Bressy, 2002; Crandell, 2005; Luedtke, 1992), and the dataset with the sample characterisations as well as the variable descriptions can be found in the SOM (Tables S2 and S3). A small hand lens of 10x magnification was used for this analysis, followed by a higher magnification analysis with resource to a Nikon SMZ25 stereomicroscope, focusing primarily on inclusions and fossil content.

Despite several caveats, especially related to the subjectivity and lack of quantitative variables (Bustillo et al., 2009), a macroscopic approach is currently still frequently used in chert raw material studies. For a comparative analysis of archaeological artefacts, other methods may be inconvenient or impossible to use, since they may be destructive and often difficult to apply to large assemblages. Macroscopic analyses have the advantage of being less costly and easy to apply. Establishing a reliable macroscopic characterisation and understanding the potential of macroscopy to differentiate between cherts, outcrops and formations is essential for comparative studies between geological samples and archaeological assemblages and obtaining preliminary results. By then combining the macroscopic analysis with a petrographic analysis, other studies have shown that the subjective component of this approach can be minimised (Bustillo et al., 2009).

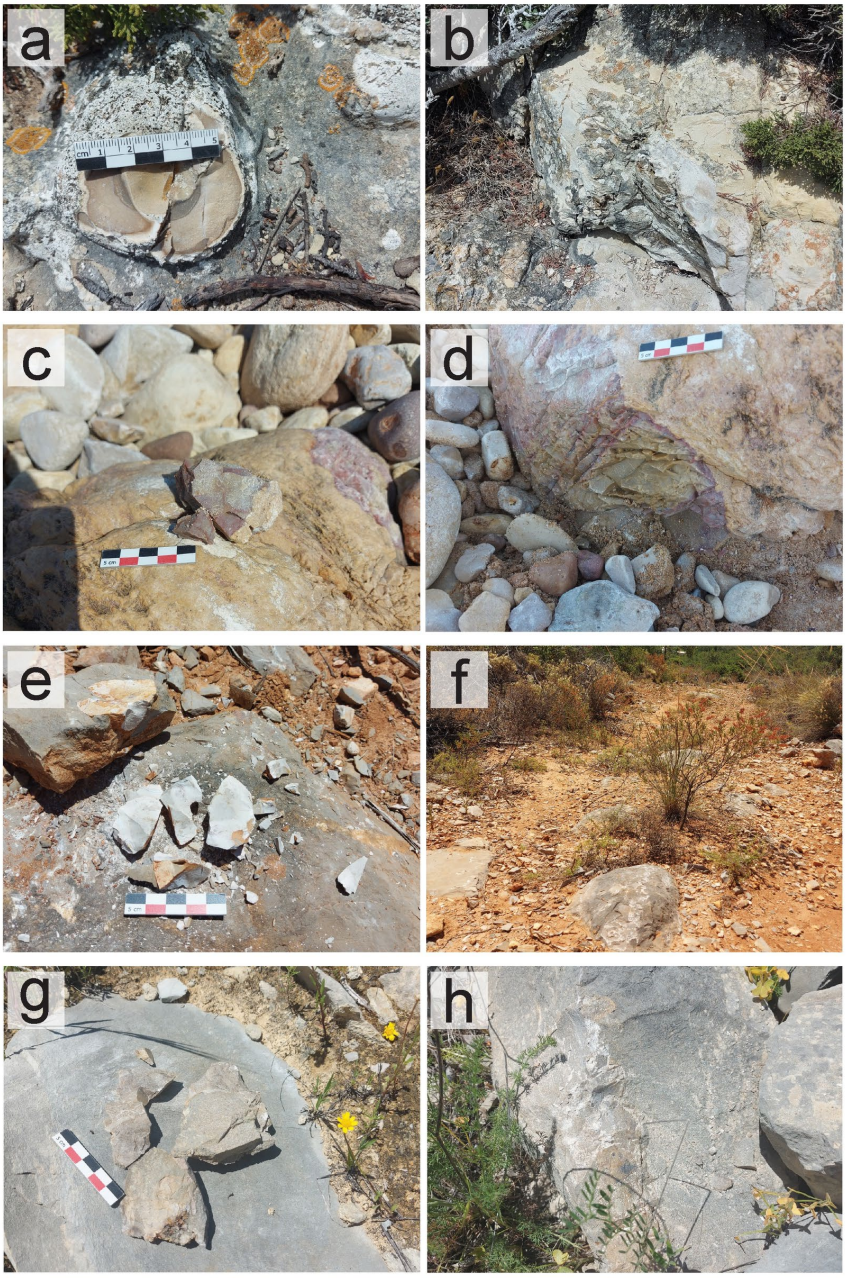

Figure 2.2. Recovered geological chert samples and general outcrop photos from chert-bearing formations, collected during fieldwork (2021-2022). (a) Detail of a chert nodule (SP32_FZF). (b) Chert outcrop Foz dos Fornos (FZF) (Lower Jurassic, Carixian formation) associated with sample SP32_FZF. (c) Detail of a chert nodule (SP69_MAR). (d) Chert outcrop of Praia da Mareta (MAR) (Upper Jurassic, Kimmeridgian formation) associated with sample SP69_MAR. (e) Detail of recovered chert samples (SP65_MALH) and nodules. (f) General photo of the Malhão outcrop (MALH) (Middle Jurassic, Malhão formation) associated with sample SP65_MALH. (g) Detail of recovered chert samples (SP58_JOR). (h) General photo of the Jordana outcrop (JOR) (Upper Jurassic, Jordana formation) associated with sample SP58_JOR.

The second phase of the study focused on the petrographic analysis of the geological samples. Thin sections were produced from geological samples of all formations, focusing on obtaining petrographic data that reflected the macroscopic variability. In total, 30 thin sections were produced (Table 2.1), divided into three groups: 1) 20 thin sections of geological samples from different outcrops of the Lower Jurassic and Upper Jurassic chert-bearing formations within the western section of the Algarve; 2) 9 thin sections of geological samples from different outcrops of the Malhão and Jordana chert-bearing formations, from the eastern section of the Algarve; 3) 1 thin section of a geological sample recovered from previous works, which was not identified during our survey. Although primary outcrops were prioritised, thin sections of secondary deposition samples were also produced. To compare with the thin sections from this study, other thin sections from previous studies of Jurassic outcrops from western Algarve (Ribeiro, 2005) were also consulted. All thin sections were analysed using a Nikon LV100ND or a Leica DM2500 P and following standard petrographic description (full descriptions of the variables considered for the petrographic description can be found in S3 Table).

All sample descriptions (macroscopic and petrographic) and accompanying photographs, as well as photographs and data about the outcrops are also available on a database dedicated to the LusoLit lithotheque, which can be accessed online at https://lusolit.icarehb.com/. This database will continue to be updated with the other existing samples, non-chert raw materials and future analyses. The complete R code used for all the analysis and visualizations contained in this paper is available at our online research compendium (https://doi.org/10.17605/OSF.IO/FP7TA). To produce those files, we followed the procedures described by Marwick (2017) for the creation of research compendiums to enhance the reproducibility of research. The files provided contain all the raw data used in our analysis as well as a custom R project (Wickham, 2015) holding the code to produce all tables and figures. To enable maximum reuse, code is released under the MIT license, data as CC-0, and figures as CC-BY (for more information, see Marwick, 2017).

Table 2.1. List of geological samples chosen for the petrographical study. UB – Servei de Làmina Prima, University of Barcelona (Barcelona, Spain); TSL - Thin Section Lab (Toul, France).

Sample ID	Type	Laboratory	Outcrop	Formation	Epoch	Sample collection
SP6	Covered	UB	Cabo S. Vicente	Carixian	Lower Jurassic	2021
SP7	Covered	UB	Cabo S. Vicente	Carixian	Lower Jurassic	2021
SP9	Covered	UB	Ponta dos Altos	Carixian	Lower Jurassic	2021
SP10	Covered	UB	Ponta dos Altos	Carixian	Lower Jurassic	2021
SP14	Covered	UB	Praia Belixe	Carixian	Lower Jurassic	2021
SP15	Covered	UB	Praia Belixe	Carixian	Lower Jurassic	2021
SP18	Covered	UB	Praia Belixe	Carixian	Lower Jurassic	2021
SP21	Covered	UB	Belixe Sul	Carixian	Lower Jurassic	2021
SP23	Covered	UB	Belixe Norte	Carixian	Lower Jurassic	2021
SP24	Covered	UB	Cabo S. Vicente	Carixian	Lower Jurassic	2021
SP27	Covered	UB	Cabo S. Vicente	Carixian	Lower Jurassic	2021
SP28	Covered	UB	Aspa	Carixian	Lower Jurassic	2021
SP32	Covered	UB	Foz dos Fornos	Carixian	Lower Jurassic	2021
SP33	Covered	UB	Foz dos Fornos	Carixian	Lower Jurassic	2021
SP34	Covered	UB	Ponta dos Altos	Carixian	Lower Jurassic	2021
SP34	Covered	UB	Ponta dos Altos	Carixian	Lower Jurassic	2021
SP36	Covered	UB	Ponta da Atalaia	Kimmeridgian	Upper Jurassic	2021
SP39	Covered	UB	Andorinha	Kimmeridgian	Upper Jurassic	2021
SP40	Covered	UB	Ferrel	Carixian	Lower Jurassic	2021
SP42	Covered	UB	Boca do Rio	N/A	N/A	2021
SP59	Covered	TSL	Jordana	Jordana	Upper Jurassic	2022
SP61	Covered	TSL	Peral	N/A	Upper Jurassic	2022
SP56	Covered	TSL	Jordana	Jordana	Upper Jurassic	2022
SP54	Covered	TSL	Guilhim	Malhão	N/A	2022
SP53	Covered	TSL	Guilhim	Malhão	Middle Jurassic	2022
SP58	Covered	TSL	Jordana	Jordana	Upper Jurassic	2022

SP55	Covered	TSL	Caliços	Malhão	Middle Jurassic	2022
SP50	Covered	TSL	Casal da Colina	Malhão	Middle Jurassic	2022
SP52	Covered	TSL	Casal da Colina	Malhão	Middle Jurassic	2022
RT82	Covered	TSL	Praia Belixe	N/A	N/A	<2021

2.4 Results

Eighteen outcrops (primary and secondary) were revisited or newly identified in the Algarve region. Nine are located in the westernmost territory and nine to the east (Figure 2.3). From these, 57 samples were recovered and analysed, of which 19 are isolated finds or in secondary settings (Table 2.2).

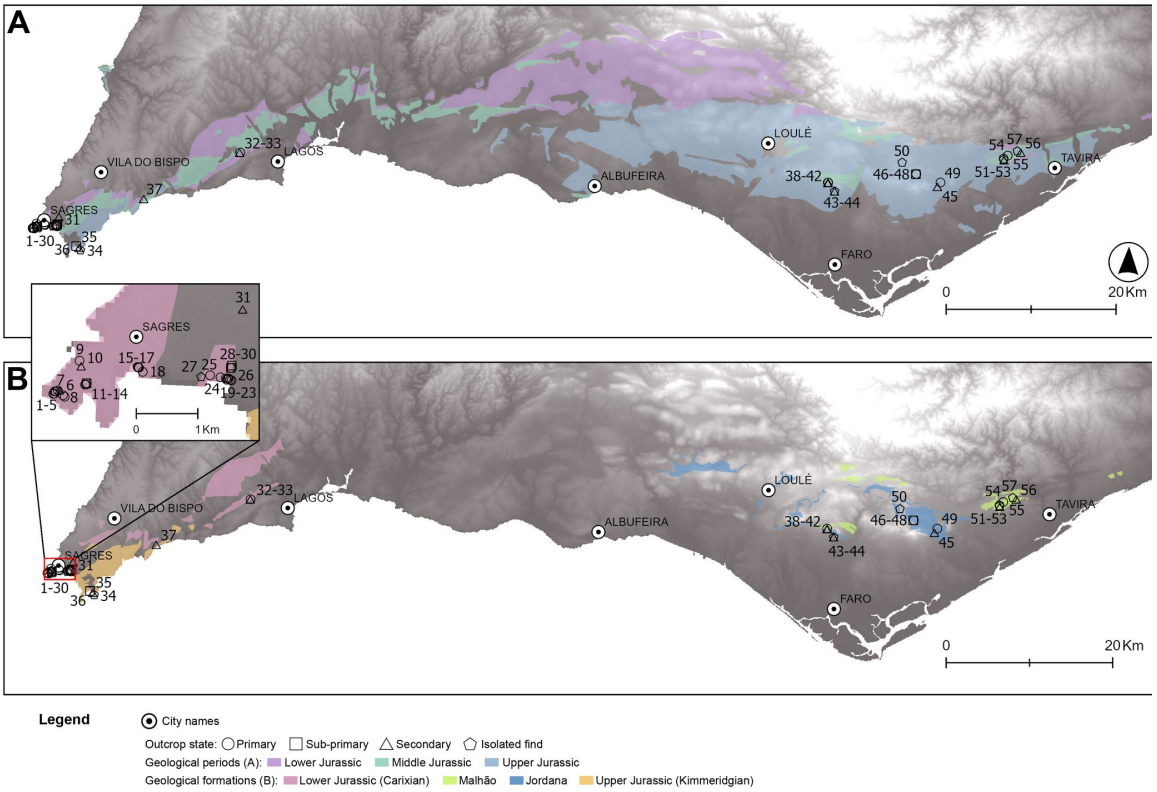

Figure 2.3. Map of southern Portugal (Algarve), with geological samples recovered during this study's fieldwork. Colours represent the chert-bearing formations in the Algarve. Numbers represent the recovered samples during fieldwork organized by formation, outcrop, and location. Lower Jurassic (Carixian) formation: 1-8: Cabo de S. Vicente (CSV); 9-10: Aspa (ASP); 11-14: Foz dos fornos (FZF); 15-18: Ponta dos Altos (PdA); 19-27: Praia de Belixe (PBX); 28-30: Belixe Sul (BLS); 32-33: Ferrel (FER). Upper Jurassic (Kimmeridgian) formation: 35: Ponta da Atalaia (PtA); 36: Praia da Mareta (MAR); 37: Praia da Andorinha (AND). Malhão formation: 38-42: Casal da colina (CdC); 43: Guilhim (GUI); 45: Caliços (CAL); 51-53: Oliveiras (OLV); 54-55: Malhão (MALH). Jordana formation: 46-49: Jordana (JOR); 50: Peral (PER). Isolated finds: 31: Belixe Norte (BLN); 34: Ponta da Atalaia (PtA); 44: Guilhim (GUI); 56: Descampado (DESCAM); 57: Pedreira (PEDR)

Table 2.2. Outcrop and nodule information for all recovered samples. The age was defined based on the location of the outcrops, taking into consideration previous research work and geological maps. Samples which were isolated or in untraceable secondary deposition settings do not have a defined geological age.

Sample ID	Outcrop name	State	Age	Chert morphology	Chert freq.	Chert variability	Chert size
SP3_CSV	Cabo S. Vicente	Primary	Lower Jurassic	Nodule/Bedded	Sporadic	Homogeneous	2-5cm
SP4_CSV	Cabo S. Vicente	Primary	Lower Jurassic	Bedded	Abundant	Homogeneous	-
SP6_CSV	Cabo S. Vicente	Primary	Lower Jurassic	Bedded	Abundant	Variable	-
SP7_CSV	Cabo S. Vicente	Primary	Lower Jurassic	Nodule/Bedded	Abundant	Homogeneous	-
SP8_PdA	Ponta dos Altos Este	Primary	Lower Jurassic	Nodule	Sporadic	Variable	5-20cm
SP9_PdA	Ponta dos Altos Este	Primary	Lower Jurassic	Nodule	Abundant	Variable	5-20cm
SP10_PdA	Ponta dos Altos Este	Primary	Lower Jurassic	Nodule	Abundant	Homogeneous	5-10cm
SP12_PBX	Praia do Belixe	Primary	Lower Jurassic	Nodule	Sporadic	Homogeneous	-
SP13_PBX	Praia do Belixe	Primary	Lower Jurassic	Nodule	Abundant	Variable	Max. 15cm
SP14_PBX	Praia do Belixe	Primary	Lower Jurassic	Nodule/Bedded	Abundant	Variable	Max. 15cm
SP15_PBX	Praia do Belixe	Primary	Lower Jurassic	Nodule/Bedded	Abundant	Homogeneous	Max. 20cm
SP16_PBX	Praia do Belixe	Primary	Lower Jurassic	Nodule	Abundant	Homogeneous	3cm
SP17_PBX	Praia do Belixe	Primary	Lower Jurassic	Nodule	Abundant	Variable	5-15 cm
SP18_PBX	Praia do Belixe	Primary	Lower Jurassic	Nodule/Bedded	Abundant	Variable	-
SP19_PBX	Praia do Belixe	Primary	Lower Jurassic	Nodule	Rare	Variable	5-20cm
SP20_BLS	Belixe Sul	Sub-primary	Lower Jurassic	Block	Abundant	Variable	-
SP21_BLS	Belixe Sul	Sub-primary	Lower Jurassic	Nodule	Abundant	Variable	3-8cm
SP22_BLS	Belixe Sul	Primary	Lower Jurassic	Nodule	Sporadic	Homogeneous	3-8cm
SP23_BLN	Belixe Norte	Secondary	N/A	-	Abundant	Variable	-
SP24_CSV	Cabo S. Vicente	Primary	Lower Jurassic	Nodule	Sporadic	Homogeneous	5cm
SP25_CSV	Cabo S. Vicente	Primary	Lower Jurassic	Nodule	Rare	Homogeneous	-
SP26_CSV	Cabo S. Vicente	Secondary	Lower Jurassic	-	Abundant	Homogeneous	-
SP27_CSV	Cabo S. Vicente	Primary	Lower Jurassic	Nodule	Rare	Homogeneous	5-10cm
SP28_ASP	Aspa	Primary	Lower Jurassic	Nodule	Sporadic	Variable	5cm
SP29_ASP	Aspa	Secondary	Lower Jurassic	-	Abundant	Variable	<5cm

SP30_FZF	Foz dos Fornos	Primary	Lower Jurassic	Nodule	Rare	Homogeneous	Max. 15cm
SP31_FZF	Foz dos Fornos	Sub-primary	Lower Jurassic	Nodule	Abundant	Variable	<5cm
SP32_FZF	Foz dos Fornos	Primary	Lower Jurassic	Nodule	Abundant	Variable	4-8cm
SP33_FZF	Foz dos Fornos	Primary	Lower Jurassic	Nodule	Abundant	Variable	4-8cm
SP34_PdA	Ponta dos Altos Este	Primary	Lower Jurassic	Nodule	Abundant	Variable	4-8cm
SP35_BLX	Belixe	Isolated find	N/A	-	-	-	-
SP36_PtA	Ponta da Atalaia	Isolated find	N/A	-	-	-	-
SP37_PtA	Ponta da Atalaia	Secondary	Upper Jurassic	-	Abundant	Variable	-
SP39_AND	Andorinha	Secondary	Upper Jurassic	-	Sporadic	Homogeneous	-
SP40_FER	Ferrel	Primary	Lower Jurassic	Nodule	Abundant	Variable	-
SP41_FER	Ferrel	Secondary	Lower Jurassic	-	Sporadic	Variable	-
SP47_CdC	Casal da Colina	Primary	Middle Jurassic	Nodule	Rare	Homogeneous	3-8cm
SP48_CdC	Casal da Colina	Secondary	Middle Jurassic	-	Rare	Variable	-
SP49_CdC	Casal da Colina	Secondary	Middle Jurassic	-	Rare	Variable	-
SP50_CdC	Casal da Colina	Primary	Middle Jurassic	Nodule	Sporadic	Homogeneous	3-5cm
SP52_CdC	Casal da Colina	Secondary	Middle Jurassic	-	Rare	Homogeneous	-
SP53_GUI	Guilhim	Secondary	Middle Jurassic	-	Sporadic	Variable	-
SP54_GUI	Guilhim	Isolated find	N/A	-	-	-	-
SP55_CAL	Caliços	Secondary	Middle Jurassic	-	Rare	Homogeneous	-
SP56_JOR	Jordana	Sub-primary	Upper Jurassic	Nodule	Abundant	Homogeneous	2-20cm
SP57_JOR	Jordana	Primary	Upper Jurassic	Nodule	Abundant	Homogeneous	2-5cm
SP58_JOR	Jordana	Primary	Upper Jurassic	Nodule	Sporadic	Homogeneous	5cm
SP59_JOR	Jordana	Primary	Upper Jurassic	Nodule	Abundant	Homogeneous	3-5cm
SP61_PER	Peral	Other	Upper Jurassic	Nodule	Sporadic	Homogeneous	2-5cm
SP62_OLV	Oliveiras	Secondary	Middle Jurassic	-	Abundant	Variable	-
SP63_OLV	Oliveiras	Primary	Middle Jurassic	Nodule	Sporadic	Homogeneous	2-15cm
SP64_OLV	Oliveiras	Isolated find	N/A	-	-	-	-
SP65_MALH	Malhão	Primary	Middle Jurassic	Nodule	Sporadic	Homogeneous	5cm

SP66_MALH	Malhão	Primary	Middle Jurassic	Nodule	Sporadic	Homogeneous	5cm
SP67_DESCAM	Cabeço Descampado	Secondary	N/A	Nodule	Sporadic	Homogeneous	-
SP68_PEDR	Pedreira	Other	N/A	-	Rare	Homogeneous	-
SP69_MAR	Praia da Mareta	Sub-primary	Upper Jurassic	Nodule	Abundant	Variable	Max. 25cm

2.4.1 Western Algarve

On the westernmost areas of the Algarve, there are mainly cherts from two different formations: Carixian formations (Lower Jurassic) and Kimmeridgian formations (Upper Jurassic, Figure 2.3). The latter can be found in primary deposition in a single known outcrop—Praia da Mareta (MAR)—or nearby, in secondary deposition settings. Lower Jurassic outcrops are more common and, for that reason, have been more studied (Ribeiro, 2005). These outcrops are heterogeneous, showing different geological characteristics and chert colours (Figure 2.4). The Lower Jurassic cherts can be grouped into three main macroscopic types based on colour (individual Munsell Colour Chart codes can be found in the macroscopic description analysis table) and presence of fossil content: 1) multi-coloured, yellow, red, light grey or purple type (MC, Figure 2.4 b and Figure 2.4 d); 2) single grey/brown type (SGB, Figure 2.4 e and Figure 2.4 f); 3) multi-coloured, yellow, red, light grey or purple with fossils type (MCF, Figure 2.4 a and Figure 2.4 c). The first two types are present in all outcrops. They are mainly characterised by dull to medium lustre and opaque translucency, although some samples were sub-translucent. The feel ranges between smooth and semi-smooth, although many of the cherts from the Belixe outcrop are distinctly rough to the touch. In the MC cherts, fossil content is present but visible only as white, red, or yellow speckling. The SGB cherts show little fossil content, barely visible with the stereomicroscope. The MCF show a large quantity of larger fossils (~1000 μm), which are easily seen by the naked eye and can be identified under the microscope.

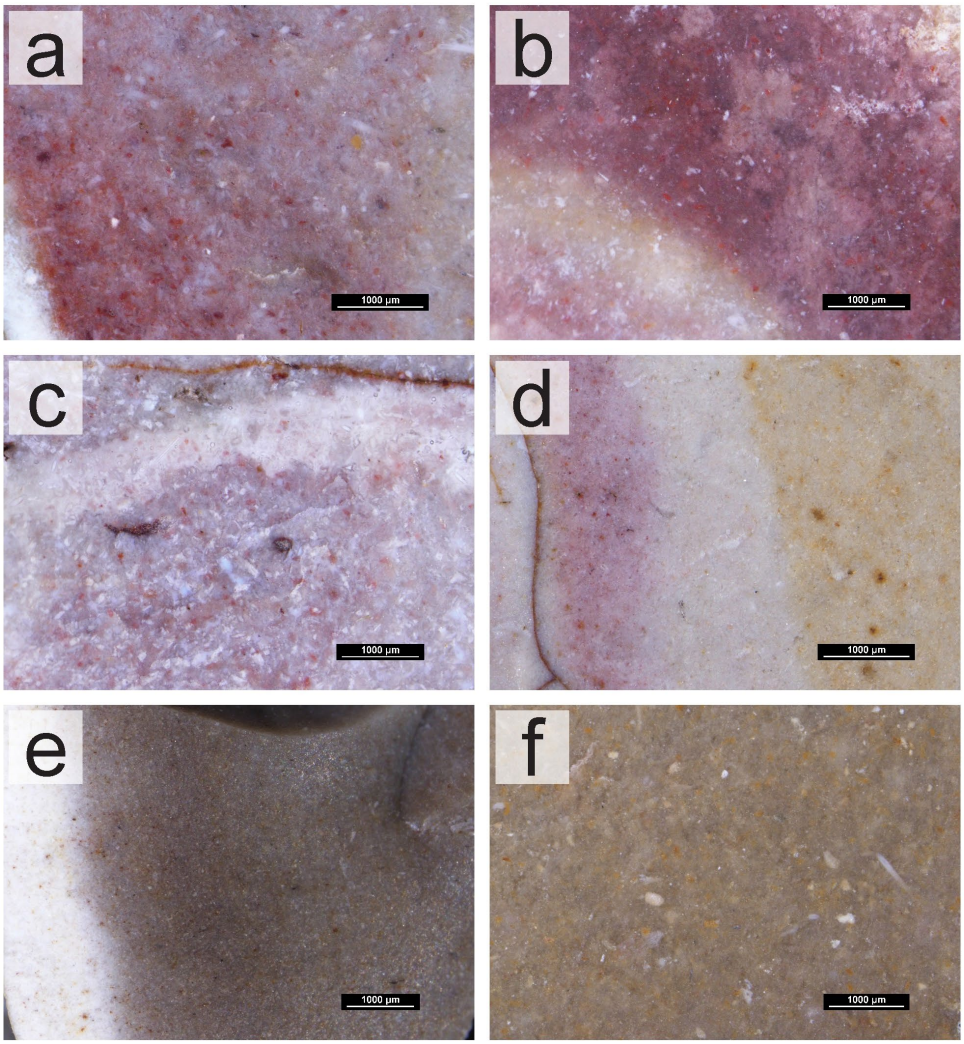

Figure 2.4. View of the macroscopic variability of the Lower Jurassic Carixian cherts (several outcrops) from western Algarve. (a) Sample SP34_PdA. (b) Sample SP14_PBX. (c) Sample SP16_PBX. (d) Sample SP30_FZF. (e) SP9_PdA. (f) Sample SP34_PdA.

Petrographically, the Lower Jurassic cherts of western Algarve are composed mainly of microcrystalline quartz, with textures that range mostly from wackestone to packstone (Figure 2.5). Dolomite is also present although in frequencies inferior to 10%. Macrocrystalline quartz and chalcedony occur in small frequencies (~5%), frequently replacing bioclasts. The presence of mica is uncommon and always below 1%. Allochems present are mostly iron oxides (ranging from uncommon to very frequent) and the presence of peloids is rare. In more than 50% of the samples, no fossils can be identified, as all fossils, albeit common to very frequent, are poorly preserved, and without any identifiable morphology. Whenever identifiable, fossils present in the sample are

echinoderms (Figure 2.5 b and Figure 2.5 c), radiolarians, sponge spicules, and bivalve shells (Figure 2.5 e and Figure 2.5 f). In all samples porosity ranges from 1-5% (vuggy type).

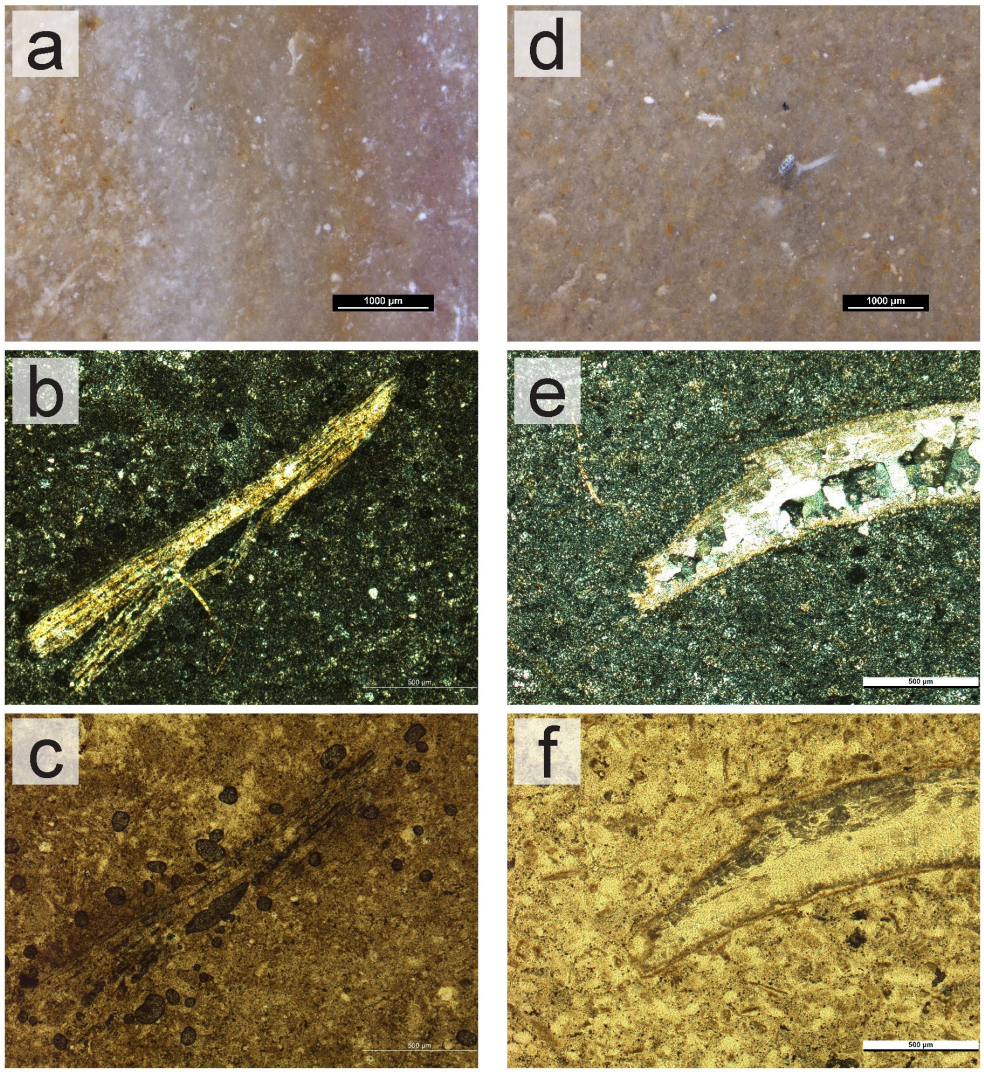

Figure 2.5. Macroscopic and microscopic view of chert samples from the Lower Jurassic cherts from western Algarve. (a) Sample SP7_CSV. Macroscopic view with a stereomicroscope. (b-c) Sample SP7_CSV. Microscopic view of thin section, XPL (b) and PPL (c). An Echinoid spine, replaced by quartz but preserving the fossil's original structure is present in the centre of the images. (d) Sample SP34_PdA. Macroscopic view with a stereomicroscope. (e-f) Sample SP34_PdA. Microscopic view of thin section, XPL I and PPL (f). Detail of a bivalve shell replaced by at least two generations of quartz: microcrystalline quartz at the edges and macrocrystalline quartz inside of the shell.

Despite the similar characteristics between these cherts, the outcrops are heterogeneous and show varying characteristics between them, which may be of importance to distinguish between chert sources within the Lower Jurassic formation. These outcrops have been divided into four groups, following the available literature: 1) Cabo de S. Vicente (CSV) and Aspa (ASP); 2) Foz dos Fornos (FZF) and Ponta dos Altos (PdA); 3) Praia do Belixe (PBX, which includes Belixe Sul, BLS), and 4) Ferrel (FER). The Cabo de S. Vicente (CSV) and Aspa (ASP) chert outcrops are characterised by abundant nodules in the natural rock banks of the cliffs, appearing as horizontal layers within the parent rock. The banks seem to be mainly dolomite or dolomitic limestones. The process of dolomitization seems to have affected the chert nodules, as they often present different levels of silicification from the peripheral areas of the nodule to the interior, which also affects the size and feel of the grain. In this case, the peripheral areas of the chert nodules are more dolomitized, with visible grain and distinctively rough to the touch, while the interior areas are more silicified and conversely finer and smoother. The nodules vary in size, ranging from small 4 cm in diameter circular nodules to bed-like groups of nodules with ~20 cm in width. At the Aspa outcrops, the nodules are less frequent and smaller. Due to the proximity to the cliffs, the visibility of the chert nodules is good, and in present times, small chunks of chert (without cortex or with small amounts of parent rock attached) accumulate in secondary deposits nearby.

Foz dos Fornos (FZF) and Ponta dos Altos (PdA) show similarities to the CSV outcrops. The nodules are visible in several banks of dolomite, dolomitic limestone, and limestone, partially covered by soil and sand. The nodules can be circular, around 5 cm in diameter, or wide, nearly 20 cm in width. Despite their size, these cherts are frequently filled with fractures that fragment the larger nodules into smaller volumes of raw material. Alike CSV, FZF and PdA also show cherts with differing degrees of dolomitization, although in apparent smaller quantities than CSV. Besides the abundant presence of primary outcrops, there are also abundant chert nodule fragments in secondary deposition, down the slope of the cliff (in the case of FZF) or at the top of the cliff, on a sand path (in the case of PdA). These are small, between 1-4 cm in width, but of easy access. Between the FZF chert and the PdA, the main differences seem to be the cortex and host rock, which show differing reactions to hydrochloric acid, the first being

dolomite or dolomitic limestone, and the second being mostly limestone, with some degree of dolomitization in certain areas.

Praia do Belixe (PBX) is characterised by the abundance of chert nodules throughout the dolomite layers of the cliff area. They are visible in certain areas of the cliff and within the rock shelters. The nodules can be small, around 5 cm in diameter, sometimes reaching more than ~30 cm in width, or bedded, as chert layers between the dolomite layers. The cherts show varying degrees of dolomitization and are mostly characterised by a coarse to semi-smooth feel and dull lustre, often showing fractures and alterations. Unlike the other outcrops, no chert nodule fragments were found close to the cliffs, and the samples could only be recovered directly from the embedded nodules in the cliff walls. Nodules scattered on the floor were only located at Belixe Sul (BLS), a primary outcrop nearly destroyed, located on a field, north of the beach area. The chert in this outcrop showed no differences from PBX, aside from the size of the nodules, which were smaller and often showed signs of post-depositional alterations. A third location for chert has been previously identified north of BLS. Belixe Norte (BLN) is located on a dirt road and an unused agricultural field. Several chert fragments were collected in this location. However, BLN is in proximity to an archaeological site and several collected samples were lithic artefacts. No larger nodules or outcrop were identified in this location. The samples recovered from the location also seem to corroborate that BLN should not be considered an outcrop, as they do not match the local cherts and rather, resemble most of the samples recovered from eastern Algarve.

Ferrel (FER), unlike the other outcrops, is located inland and away from the coast. Due to its location in a homonymous village, the state of the outcrop is poor, and all samples were either recovered as scattered nodules or from larger blocks of rock, from a partially destroyed outcrop. The proximity of an archaeological site nearby also raises questions regarding the nodules found in secondary deposition, as these may be surface finds. Despite these caveats, the recovered samples are similar to those from the other Lower Jurassic outcrops, albeit with better quality, being characterised by a shiny to medium lustre and smooth to semi-smooth feel. All surface fragments and nodules were small, with around 2 to 3 cm of width which may be explained by the state of the outcrop.

Contrasting with the diversity and quantity of the Lower Jurassic outcrops, there is only one identified outcrop for Upper Jurassic cherts in western Algarve, located at

Praia da Mareta (MAR) and abundant, or in a secondary deposition at Ponta da Atalaia (PtA). The Upper Jurassic cherts are very similar to the Lower Jurassic, with dull to medium lustre and grey/purple colours (Figure 2.6 a). The translucency ranges from opaque to areas where the chert is translucent. This translucency may be a significant difference to distinguish between outcrops. Petrographically, the cherts are also similar to the Lower Jurassic ones. The only identifiable difference is the presence of calcispheres. All samples from the MAR and PtA outcrops seen under the petrographic microscope showed the presence of abundant calcispheres (Figure 2.6 b and Figure 2.6 c), which is not always apparent with the stereomicroscope. Based on the presence of calcispheres, we may also consider the samples recovered at Andorinha (AND) to be Upper Jurassic (Figure 2.6 e and Figure 2.6 f), which were uncommon and scattered at the top of the cliffs by the beach.

At Praia da Mareta the nodules are only easily accessible on the beach, where large boulders falling off the cliff (~1 m in diameter) are transported by the waves. Several chert nodules of different sizes can be found in the host rock washed ashore, ranging between 2 cm to 20 cm in diameter. The quality of the chert also varies, possibly related to different dolomitization stages of the nodules, although this may also be influenced by chemical and physical alterations to the chert. At Ponta da Atalaia the chert can be found atop the cliffs, with rare nodules scattered on the floor.

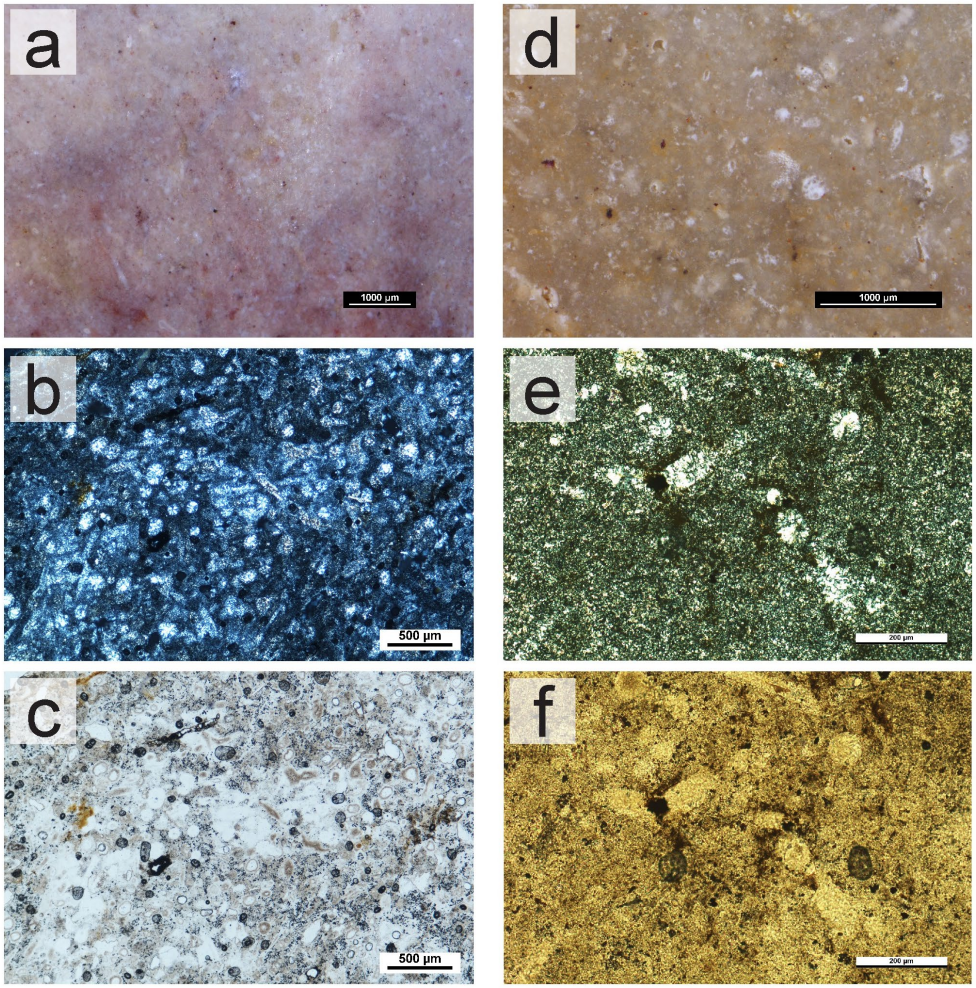

Figure 2.6. Macroscopic and microscopic view of chert samples from the Upper Jurassic cherts from western Algarve. (a) Sample SP36_PtA. Macroscopic view with a stereomicroscope. (b-c) Sample SP36_PtA. Microscopic view of thin section, XPL (b) and PPL (c). Several unidentifiable fossils can be seen in the photo, along with calcispheres. (d) Sample SP39_AND. Macroscopic view with a stereomicroscope. (e-f) Sample SP39_AND. Microscopic view of thin section, XPL I and PPL (f). A small amount of calcispheres is present in the image, along with few unidentifiable fossils replaced by quartz/chalcedony.

2.4.2 Eastern Algarve

On the eastern part of the Algarve, chert-bearing known formations are from the Middle and Upper Jurassic, known as the Malhão formation and the Jordana formation, respectively. The Malhão formation chert (Middle Jurassic) was identified in three outcrops: 1) Casal da Colina (CdC); 2) Oliveiras (OLV); and 3) Malhão (MALH). Whenever in a primary outcrop, this chert was homogeneous. Secondary deposits were also identified—Casal da Colina (CdC), Guilhim (GUI), Caliços (CAL) and Oliveiras (OLV) and were located in recent waterlines and slope deposits, and the cherts were often characterised by intense post-depositional alterations (in these cases, it was not possible to confirm the outcrop location). In the Malhão formation outcrops, the nodule frequency varied from common to abundant. The nodules are roundish, ranging between 3 to 5 cm in maximum width. In all cases, access to the outcrops was easy. Although the host rock was hard, several chert nodules could be collected from the surface, accumulating further down in gentle slope deposits. The Malhão cherts show two differing macroscopic characteristics: pink/reddish/light grey cherts (Figure 2.7 b) and grey cherts (Figure 2.7 a). In general, they are both characterised by a dull to medium lustre, opaque to sub-translucent translucency, and smooth to semi-smooth feel. They are easily identifiable through the high amounts of macroscopically visible inclusions, which look like white speckling in plain sight. Under the stereomicroscope, several round fossils and long, spicule-like shapes can be identified.

The petrographic analysis shows that the Malhão formation cherts are characterised by a wackestone texture and composed of microcrystalline quartz (85-95%). Dolomite is also present (10-5%), as well as chalcedony and macrocrystalline quartz (<5%) frequently replacing fossils. Identified allochems are oxide patina, ranging from very frequent to uncommon. A high variety of identifiable fossils (although all are poorly preserved (Figure 2.7) were also identified. These fossils are sponge spicules (Figure 2.7 e and Figure 2.7 f), radiolarians, ostracods (Figure 2.7 c and Figure 2.7 d), echinoderms, calcispheres, and possibly tentaculites. Porosity in the samples occurs in small frequencies (<5%), of vuggy type.

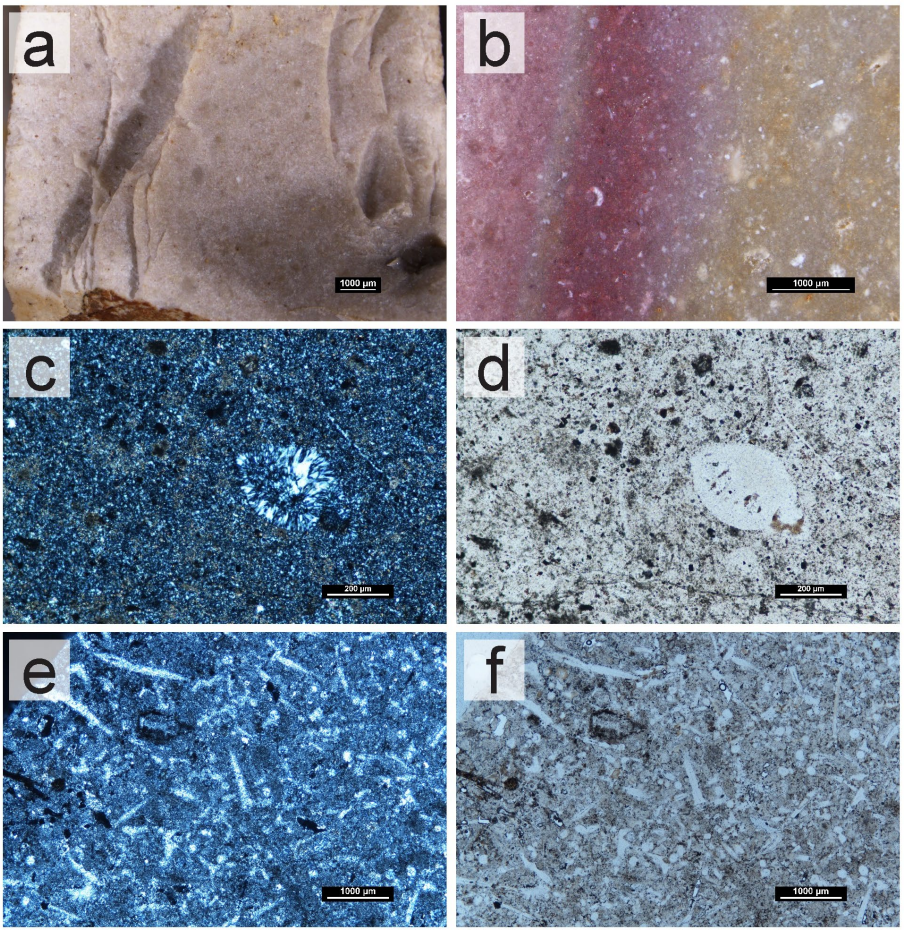

Figure 2.7. Macroscopic and microscopic views of Middle Jurassic chert samples from the Malhão formation. (a) Sample SP50_CdC, macroscopic view with a stereomicroscope. (b) Sample SP62_OLV, macroscopic view with a stereomicroscope. (c-d) Microscopic view of SP50_CdC, XPL (c) and PPL (d). Detail of a fossil (possibly an Ostracod), replaced by two generations of chalcedony (1st generation in the outer edges and 2nd generation replacing the inside). (e-f) Microscopic view of SP54_GUI, XPL (e) and PPL (f). General view of the thin section. Several fossil ghosts can be seen. Despite the poor preservation, it may be possible to identify a few fossils based on the size and morphology: 1) calcispheres or recrystallized radiolarians; 2) monaxon spicules pointed at one end.

The Jordana formation chert (Upper Jurassic) was identified in one area in the Algarve (Figure 2.3), in an outcrop of the same name (JOR). Whenever in a primary outcrop, the chert was homogeneous, although alternated with nodules of other lithologies within the host rock. No chert was identified in any secondary deposits, which might be related to the anthropic alteration of the landscape. Smaller nodules broken from the parent rock were identified near the primary source in a field. Whenever embedded in the parent rock, the nodules varied in size (~1-10 cm) and were abundant, with a high level of difficulty in their removal, due to the hardness of the parent rock. The cherts show little macroscopic variability between nodule and outcrop. They are

grey/brown (with visible yellow inclusions) (Figure 2.8 a and Figure 2.8 b). Within nodules, however, the cherts are heterogeneous, with dull and shiny or smooth and semi-smooth feel areas. Some of the nodules also show variability of translucency, with translucent areas, with a very fine grain, and little presence of visible inclusions. The petrographic analysis shows that the cherts range from a wackestone to packstone texture (Figure 2.8), which was already seen macroscopically. They are composed mostly of microcrystalline quartz (90-99%), with the presence of fibrous chalcedony (1%) replacing the fossils and dolomite (1%), as well as negligible percentages of other minerals. Present allochems are iron oxides, ranging between very frequent to common. Albeit frequent, fossils are poorly preserved in general, with a few being identifiable: calcispheres (Figure 2.8 c and Figure 2.8 d), bivalve shell (Figure 2.8 e and Figure 2.8 f), sponge spicules, ostracod, echinoderms, and gastropod. Porosity is small (~1%) of vuggy type.

2.4.3 Other outcrops

It is important to note that the aforementioned chert geological samples represent the chert variability of the identified chert-bearing formations and outcrops. However, a small number of outcrops described in regional geological maps were not identified or were not accessible. This includes four outcrops: 1) a Lower Jurassic outcrop with chert micronodules which was identified through a geological profile (Oliveira, 1992); 2) a Middle Jurassic outcrop located at the easternmost section of the Algarve with partially dolomitized clasts and chert nodules (Oliveira, 1992); 3) several unprospected locations from previous geoarchaeological works, all related to the Peral Anticline and reaching from central to eastern Algarve; 4) a possible chert exploitation archaeological site located on top of a chert source (Monte do Cerro), in eastern Algarve which was not identified and is possibly inaccessible (Bicho et al., 2003). All of these unidentifiable outcrops are located in the central or eastern portion of the Algarve. This may be related to the frequent landscape changes occurring due to agriculture or the population of previously uninhabited areas, which seldom occurs in western Algarve by the cliff areas, where most outcrops are located.

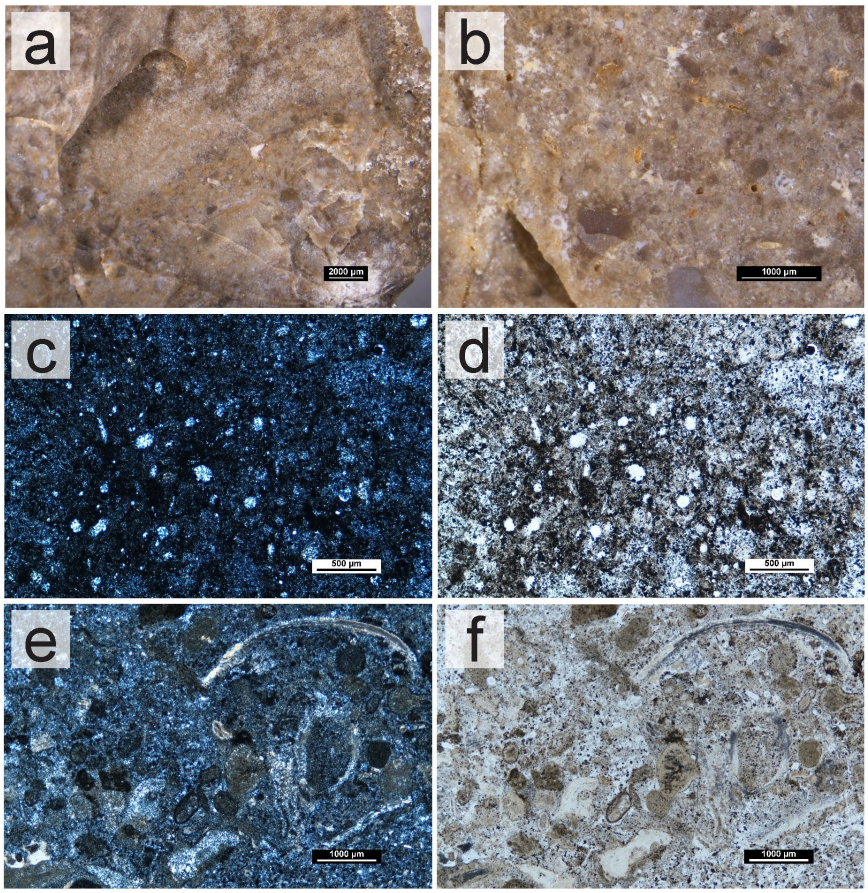

Figure 2.8. Macroscopic and microscopic views of the Upper Jurassic chert samples from the Jordana formation. (a) Sample SP58_JOR, macroscopic view with a stereomicroscope. (b) Sample SP59_JOR, macroscopic view with a stereomicroscope. (c-d) Microscopic view of SP56_JOR, XPL (c) and PPL (d). General view of calcispheres in an area of the chert characterised by a large concentration of oxide patina and opaques. (e-f) Microscopic view of SP58_JOR, XPL (e) and PPL (f). General view of the thin section. A large bivalve shell fragment is visible at the top.

2.5 Discussion

The survey work and analyses of the collected geological samples show that the south of Portugal has a high potential for chert raw material studies. The presence of chert-bearing geological formations throughout the Algarve would provide several possibilities for sourcing and procurement whenever groups moved throughout the territory. This is further important when we consider the geology of this region.

The geology of the Algarve itself may have played an important part in how groups procured their raw materials, specifically, their chert, a task that has been identified as essential for hunter-gatherer groups. To the south, communities would only have access

to chert-bearing outcrops down to the coast. To the north, the mountain range would not only have provided no chert nodules but may have also hampered the movement of populations, forcing groups to move east and west instead of north or south. This movement may have facilitated the gathering of cherts from different formations within the Algarve, posteriorly then brought into the sites. Especially for Middle and Upper Palaeolithic occupations, understanding the sources of chert in the Algarve may provide data about where in the territory these groups were sourcing their chert raw materials, and how they were using the territory having in consideration the region's natural barriers and consequent distribution of resources. Although this topic remains unexplored, this study stands as a further step to tackle these questions in the Algarve, as it may provide the necessary basis for comparative studies with archaeological assemblages.

However, tracking these movements and procurement patterns is only possible if the cherts from the different formations and outcrops can be traced back to their sources. This presented itself as the first caveat for this type of study, since for the Algarve, for example, all cherts formed in Jurassic formations in pelagic environments. Despite the similar formation environments, in general, there seem to be relevant differences between the cherts of different formations and periods. This is further relevant given the fact that they are geographically distant. Within formations, however, there are no discernible differences, both at a macroscopic and petrographic level, as these do not seem to be useful to distinguish between outcrops. This is most obvious on the Lower Jurassic formation of western Algarve. The identified chert groups, which varied mostly in colour and fossil content, are present in several outcrops from this formation. In this region, the variables which may be better used to understand which outcrops were visited may be the quality (differing levels of dolomitization, presence/absence of fractures or even size of grain) and size of the nodules. The latter, for example, is an important variable in the Praia do Belixe outcrops, which show the largest volumes of rock, even if the chert's quality is worse than some other available, smaller nodules. Size may be used in conjunction with other technological data, to understand whether different nodules were being explored differently based on their size, or their procurement was being preferred in relation to other smaller nodules in possibly closer outcrops in the region. The Upper Jurassic nodules of western Algarve also show larger

volumes than those from the Lower Jurassic. Translucency also seems to be a good macroscopic indicator to distinguish between western Algarve Lower and Upper Jurassic cherts, since the latter are characterised as sub-translucent.

However, for a reliable distinction between the Lower Jurassic and the Upper Jurassic cherts, petrographic analyses and the identification of calcispheres may be necessary. The differences identified among the cherts of the various formations can be seen both at a macroscopic and petrographic level. Given the formation settings, petrographically, all the cherts from the Algarve are fairly homogeneous—marine origin, in limestone or dolomitic limestone rocks, all formed during the Jurassic. The use of specific fossils for the identification of the cherts is also difficult since these are often not well preserved enough to allow the identification of species that may connect a group of cherts. The size, frequency, and preservation state of the fossils seem to be, then, one of the defining criteria for discerning cherts from different formations, and thus, different geographic areas. These characteristics seem to be observable macroscopically, as well, allowing the cherts from the three different areas and formations—West (including the Lower Jurassic and Upper Jurassic formation cherts of western Algarve), Jordana, and Malhão—to be differentiated without the need for thin sections (Figure 2.9). An exception might be the distinction between the cherts from the West and Malhão. The reddish cherts from Malhão are visually indistinguishable from those from the West with a higher fossil content. The grey cherts of the Malhão Middle Jurassic formation do show a higher concentration of visible round fossils, however the distinction is only possible when seen under the stereomicroscope and on a fresh surface, which might hamper the classification of archaeological materials. These distinctions are especially important for archaeological collections, especially those which may be small, with small artefacts, or for the study of older collections to which other (destructive) means of analysis may not be applied.

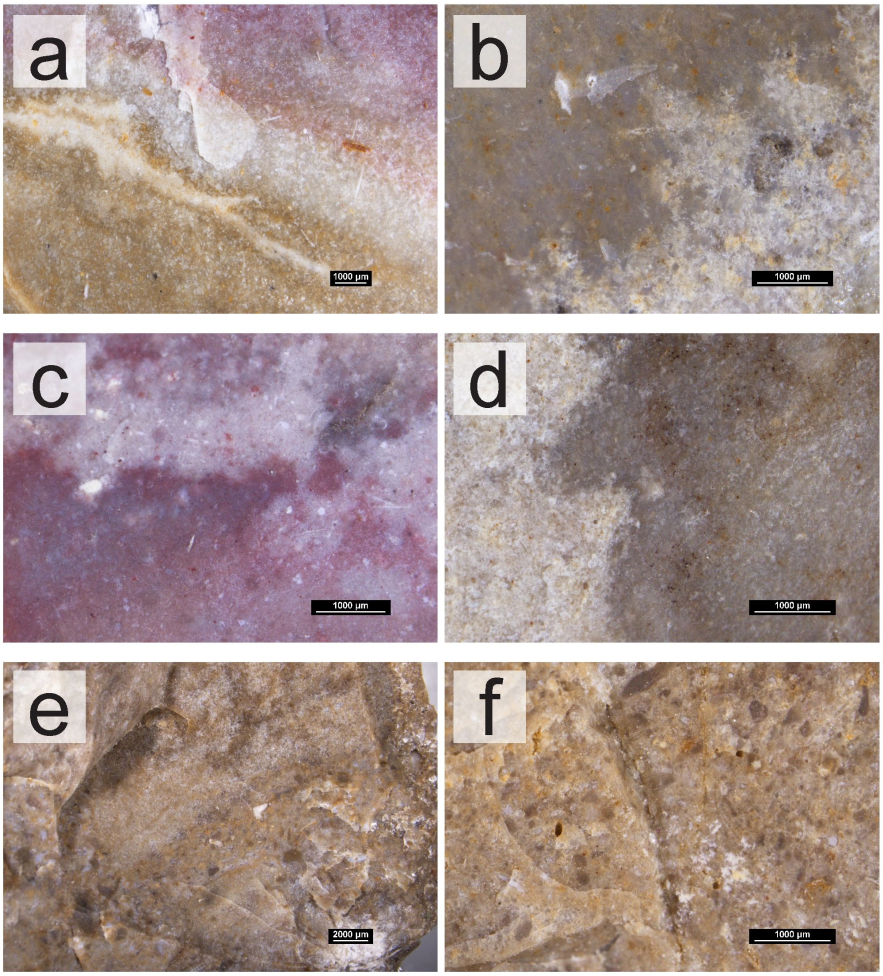

Figure 2.9. Comparison between the cherts of different formations in the Algarve, organised by geological age and formation. (a-b) Lower Jurassic (Carixian formation) chert samples under the stereomicroscope. (c-d) Middle Jurassic (Malhão formation) chert samples under the stereomicroscope. (e-f) Upper Jurassic (Jordana formation) chert samples under the stereomicroscope.

These data seem to confirm the potential of a macroscopic analysis to study the cherts of the Algarve. Albeit applying different methodologies, such as petrographic analyses, to these cherts is a way of completing the petrographic study of a collection, reliably applying mostly a macroscopic analysis to the assemblages coming from southern Portugal helps tackle issues such as the destructiveness, costliness, and time consumption of some methods. Our study was able to provide a more detailed reference collection for chert outcrops in the Algarve, which will allow us to test models about raw material procurement and use in a multilayered archaeological site like Vale Boi.

There are, however, some noteworthy caveats in this type of study. Landscapes have changed through time, both naturally and with the influence of modern society.

House constructions, agricultural fields, and roads, for example, have modified the landscape, possibly altering the availability and visibility of raw materials. Other natural processes, such as the development of biomantle or soil cover may also hamper raw material visibility in the landscape. Similarly, environmental changes may have had an impact on raw material availability, through its impact on surface processes which expose, erode and transport the raw materials (Pereira and Benedetti, 2013). As such, it is important to keep in mind that current raw material sources, and specifically chert ones which may be subtly visible in the landscape, may not correspond to the sources which were available in the past.

Another caveat regarding chert sources, especially in a geographic area like the Algarve, is the possibility of some outcrops being submerged. Previous studies have identified the existence of Jurassic lithologies on the west coast, submerged by water (Terrinha et al., 2006). These were mainly surveys done by oil companies which were able to obtain the submerged stratigraphy on the southwestern coast of Portugal and that revealed Jurassic limestones and dolomites, although the presence of chert is not described and remains unknown. Whether these submerged lithologies are different from the currently emerged ones is also uncertain. These studies also revealed that Jurassic lithologies were covered by more recent geological layers, including Pliocene and Pleistocene layers, thus forming before and/or during Palaeolithic occupations of the territory (Terrinha et al., 2006). In times when the sea level was similar to the current one, the submerged lithologies would not have been accessible, even during low tide.

However, during periods when the sea level was lower due to water freezing in the polar caps, as during the LGM for example, large portions of the coast that had been submersed would have been accessible. During this period, in Portugal, the coast would probably be close to the continental platform, ~120 m below the sea level (Dias et al., 1997; Dias et al., 2000). Specifically in western Algarve, the coastline may have been displaced ~10-15 km offshore from the present coastline (Bicho and Haws, 2008). Although currently unknown, it may be possible that during periods like the LGM, limestone and dolomite Jurassic lithologies, with chert nodules, might have been exposed and available. When studying chronologies characterised by cold and harsh climatic conditions with impacts on sea level changes and mixed with coastal uplift events, it is relevant to keep in mind that the chert variability present in the current coastline may

not necessarily reflect the variability in the past. Despite these caveats, our data raises the possibility of understanding whether this new portion of landmass altered the raw material procurement patterns of these groups, or added new resources which had been previously unavailable. Studies that compare Gravettian and Magdalenian assemblages (with higher mean sea-levels, and possibly even similar to current coastlines) to Proto-Solutrean and Solutrean assemblages (with LGM low mean sea-levels), within one single site, may give new insights into this question.

2.6 Conclusion

In this study we identified several sources of chert nodules in southern Portugal and characterised the regional cherts, which were of critical importance for hunter-gatherer communities during the Late Pleistocene. For this we applied a two-step raw material analysis approach, composed of macroscopic and petrographic analyses.

The results show the presence of four different chert formations, dispersed in western and eastern Algarve. Within most formations, there is variability in the nodules and the outcrops. There are however identifiable macroscopic and petrographic differences between formations which allow their distinction. Although the petrographic analysis is essential to identify the fossils present in the chert, a macroscopic approach seems to be pertinent for a quick and inexpensive analysis to distinguish between cherts of the different formations.

The presence of chert sources in the Algarve region, with distinguishable characteristics between formations, which may be analysed preliminarily through macroscopic approaches, shows the potential for chert raw material studies of archaeological sites in this key area. Further steps in our study will include the use of the data gathered in the present study and the completed LusoLit lithotheque to study chert use from multi-component sites with Upper Palaeolithic chronologies such as Vale Boi, and participate in the discussion of human adaptations throughout the Late Pleistocene. Furthermore, future approaches include the use of geochemical methods to further characterise these cherts and the integration of the resulting data in the online database.

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3. Within and beyond: chert procurement patterns during the Upper Palaeolithic in southwesternmost Iberia

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Abstract

Analyses of raw materials and the distinction between local/regional and long-distance sources have proven invaluable for understanding the extensive movements, interactions, and social networks during the Upper Palaeolithic in the Iberian Peninsula. However, unlike other parts of Iberia, research on the management and acquisition of raw materials in the south and west of Iberia remains relatively underdeveloped. Despite significant knowledge about the technological practices of Palaeolithic hunter-gatherers from southern Portugal, particularly from studies conducted at the site of Vale Boi, there is a noticeable lack of focus on raw materials management. This paper presents the first comprehensive characterisation of chert raw materials from the Gravettian, Proto-Solutrean, and Solutrean occupations at Vale Boi, using both macroscopic and petrographic techniques. Our study reveals that the majority of chert found at Vale Boi originates locally, within a 20 km radius. However, a non-negligible portion of the chert

comes from non-local sources, indicating >200 km raw material circulation from central Portugal and southern Spain.

keywords: Upper Paleolithic; Iberian Peninsula; Lithic raw materials; Petrography

3.1 Introduction

Knappable raw materials play a crucial role in understanding the mobility and lifeways of past hunter-gatherers, given the ubiquitous presence of lithic artefacts throughout Prehistory. More than mere rocks with which stone tools were produced, the management of these resources is intimately connected to a group's technological, social, and cultural organisation, potentially influencing the group's overall survivability (Binford, 1979; Bleed, 1986; Bousman, 1993; Gould and Saggers, 1985; Oestmo, 2017; Torrence, 1983).

Several key topics in the study of hunter-gatherer behaviour and organisation have been explored in different geographic regions and chronological periods through raw material analysis, such as modalities of procurement and mobility strategies (Ambrose and Lorenz, 1990; Binford, 1979; Binford and Stone, 1985; Gould, 1985; Gould and Saggers, 1985; Kuhn, 1991; McCall, 2007), occupation types and their duration (Kuhn, 2004; Surovell, 2009), the establishment and dimension of social networks (Whallon, 2006), as well as exchanges between groups or individuals (Gamble, 1999). These analyses are often achieved by systematically characterising geological and archaeological raw materials and establishing correlations between samples from both origins. The ultimate aim is to identify the corresponding sources, enabling, for example, a precise differentiation between local and non-local raw materials, and examine their distribution within a site over different occupations and periods.

These approaches and concepts have also been extensively and successfully applied to the study of lithic assemblages from prehistoric archaeological sites in the Iberian Peninsula (e.g., Aubry et al., 2016; Aubry and Igreja, 2009; Costa et al., 2022; García-Rojas et al., 2021; Gómez de Soler et al., 2020; Herrero-Alonso et al., 2020; Matias, 2016; Nocete et al., 2005; Ortega, 2003; Pereira et al., 2022, 2021; Pereira et al., 2016a; Ramacciotti et al., 2022; Rodríguez et al., 2011; Sánchez de la Torre et al., 2023; Soto,

2016), and contributed to understanding how different groups explored and managed the available lithic resources.

In this context, raw material analyses and the distinction between local, regional and long-distance sources have been instrumental in tracing extensive movements, contacts, and social networks throughout the Upper Palaeolithic (UP) throughout Iberia. Noteworthy examples include studies in northwestern Iberia (Galicia) during the Solutrean period (Lombera-Hermida et al., 2016), northern Iberia (Asturias) during the Magdalenian occupations at Las Caldas (Corchón Rodríguez et al., 2016), northeastern Iberia (Catalunya) during the Aurignacian and Gravettian periods at Arbreda cave (Marreiros et al., 2016; Ortega, 2003), northern Portugal during the Gravettian/Solutrean periods in the Côa Valley (Aubry et al., 2016, 2004), and inland central Iberia (Guadalajara) during the Proto-Solutrean and Solutrean periods at Peña Capón (Sánchez de la Torre et al., 2023). Ultimately, the recognition of these connections has broadened our comprehension of mobility and social organisation during the UP in Iberia, illustrating a vast interconnected territory.

However, in contrast to other areas of Iberia, and despite the potential of raw material studies to shed light on the lifeways and organisational structures of Palaeolithic hunter-gatherers, research on the procurement and management of raw materials during the UP in southern and western Iberia remains in its initial stages. Specifically, in southern Portugal, even though there is considerable knowledge about the technological organisation of Palaeolithic hunter-gatherers—largely due to research conducted at the Vale Boi archaeological site (e.g., Belmiro et al., 2021; Bicho et al., 2013; Cascalheira, 2010; Cascalheira and Bicho, 2013; Horta et al., 2019; Marreiros et al., 2015)—raw material studies are notably infrequent and use mainly macroscopic methodologies.

This situation is attributed to the absence of a detailed and comprehensive characterisation of regional lithic resources in the Algarve region (southern Portugal) and the subsequent lack of a complete reference collection produced by complementing characterisation methodologies, which is a critical component for conducting raw material studies. Such efforts are particularly crucial for distinguishing between local and non-local raw materials and for understanding variations within the archaeological record (Pop, 2015; Surovell, 2009).

Recently, we have made significant strides by introducing such a reference collection and establishing a framework for raw material studies in the region, through a detailed macroscopic and petrographic database of chert resources in the Algarve region (Belmiro et al., 2023). This initiative paves the way for systematic investigations into raw material procurement strategies during the Upper Palaeolithic, especially concerning the Vale Boi site, where previous raw material studies have already shown complex patterns of chert procurement and management. These preliminary studies at Vale Boi, employing only macroscopic methods, pointed to a predominant use of local cherts (Bicho et al., 2013; Pereira et al., 2016a; Verissimo, 2004), likely originating within a 16 km radius and reflecting embedded procurement strategies (Pereira et al., 2016a). To a lesser extent, non-local cherts were also identified throughout the various UP occupations (Bicho et al., 2013; Pereira et al., 2016a; Verissimo, 2004), pointing to extended sourcing networks, possibly involving sourcing from other regions of southern Portugal and southern Spain. The presence of chert from the Cretaceous formations of central Portugal has also been suggested (Bicho et al., 2013).

These results highlight the potential for systematic raw material studies at the site to shed light on the lithic resource procurement strategies, mobility patterns, and social networks of the hunter-gatherer groups of southwestern Iberia throughout the UP.

Vale Boi stands as a key archaeological site for this study since it is currently the only site in southern Portugal with a long-term occupation spanning most of the UP and allowing the exploration of raw material procurement and mobility trends through time (Cascalheira et al., 2017b). It also holds a pivotal role in the study of UP adaptations on the Iberian Peninsula, providing invaluable insights into the subsistence and technological strategies of hunter-gatherer populations (Belmiro et al., 2021; Bicho et al., 2013; Cascalheira, 2019; Cascalheira et al., 2017b; Horta et al., 2019; Manne et al., 2012; Marreiros et al., 2016; Pereira et al., 2016a).

Furthermore, previous studies have highlighted the role of Vale Boi in understanding different patterns of territory exploitation and contact with other regions of Iberia throughout the UP. During the Solutrean, Vale Boi has been interpreted as an important connection point between the core Solutrean areas of central Portugal and southern Spain, making it a key site for identifying extended social networks that promoted the exchange of information and culture (Cascalheira et al., 2017b; Cascalheira,

2013; Cascalheira and Bicho, 2013). On the contrary, techno-typological studies from the Gravettian occupations of Vale Boi instead show marked differences between regions and suggest a more limited circulation of people and information in southern Iberia (Marreiros and Bicho, 2013).

Based on the notions that a) during the Solutrean Vale Boi served as a connection point between different regions which may have promoted the exchange of information and culture, including raw materials from long-distances; and b) the limited circulation of people during the Gravettian may have isolated groups occupying Vale Boi, making them mostly reliant on the available local or regional resources, we propose a set of hypotheses and expectations regarding chert procurement and human mobility throughout the UP at Vale Boi. On one hand, it would be expected that Solutrean occupations are characterised by the predominant use of local raw materials but with a considerable percentage of cherts obtained from long-distance sources, possibly through exchange with different groups in Iberia. Conversely, it would be expected that Gravettian occupations would be mostly composed of local cherts, with a more limited presence of long-distance cherts.

To investigate the applicability of these patterns to the procurement and circulation of lithic raw materials, and to examine the prevailing hypotheses concerning UP mobility and social network exchanges, this paper focuses on the following questions: 1) what types of chert were the hunter-gatherers of Vale Boi using and where did they come from?; 2) are there different patterns of chert use throughout time?; 3) and if so, how can these be related to patterns of land use and the circulation of people/ideas, as suggested through technological studies of the same lithic assemblages? As a result, our study presents the first comprehensive characterisation of chert raw materials, through macroscopic and microscopic analysis, of UP occupations in southwestern Iberia, derived from the Gravettian, Proto-Solutrean, and Solutrean (c. 32-19 ka cal BP) occupations at Vale Boi.

3.1.1 Site description

Vale Boi is located on the western coast of the Algarve region in southern Portugal, within a small valley that extends southward to the Atlantic coast, approximately 2 km away (Figure 3.1 b). It is bordered by limestone outcrops that form rock shelters facing

west and southwest (Bicho et al., 2013; Bicho et al., 2012, 2007; Cascalheira et al., 2017b; Cascalheira and Bicho, 2013; Manne et al., 2012; Manne and Bicho, 2011). The site extends for more than 10,000 sq meters along the slope of the valley, through which three main areas were excavated between 2000 and 2019: Slope, Terrace, and Shelter. For this study, the chosen areas were the Terrace and Shelter areas (see Section 2 Materials and Methods).

The Terrace encompasses occupations from the UP to the Early Neolithic, resulting in the identification of eight main lithostratigraphic units. The UP sequence includes several occupations attributed to the Gravettian (levels 8 to 6) between c. 32 and 27 ka cal BP, Proto-Solutrean (levels 5 to 4E) between c. 26 and 24 ka cal BP, and Solutrean (level 4D, 4C, 4C, 4 and Lower 3) between c. 24 and 20 ka cal BP (Belmiro et al., 2021; Cascalheira et al., 2017b; Cascalheira and Bicho, 2013).

The Shelter area shows four main lithostratigraphic units, with Magdalenian, Solutrean and Gravettian occupations. From these, the Solutrean levels show the most intensive occupation, with three, well-preserved, archaeological horizons (layers C to A) and dated to c. 24-22 ka cal BP (Cascalheira et al., 2017b, 2013; Cascalheira, 2010). These occupation levels were identified under blocks of limestone, which collapsed from the rock shelter ceiling (Cascalheira, 2010).

Both these areas have been previously interpreted as seasonal residential camps, repeatedly used for extended stays, due to the abundance of lithic debitage, stone tools, heat-cracked rocks related to grease rendering activities, large quantities of faunal remains (both marine and terrestrial) and the presence of ornaments and portable art (Manne et al., 2012). The analysis of lithic assemblages and retouched frequency of lithic assemblages from the Terrace and Shelter areas also corroborate this interpretation (Cascalheira et al., 2017b; Cascalheira, 2010; Marreiros, 2009). Cascalheira et al. (2017b) show that, with the exception of the Early Gravettian occupations of the Terrace area and Magdalenian occupation of the Shelter, all other UP occupations are composed of high-density assemblages with low degree of retouch, correspondent to a residential base-camp occupation, for extended periods of time.

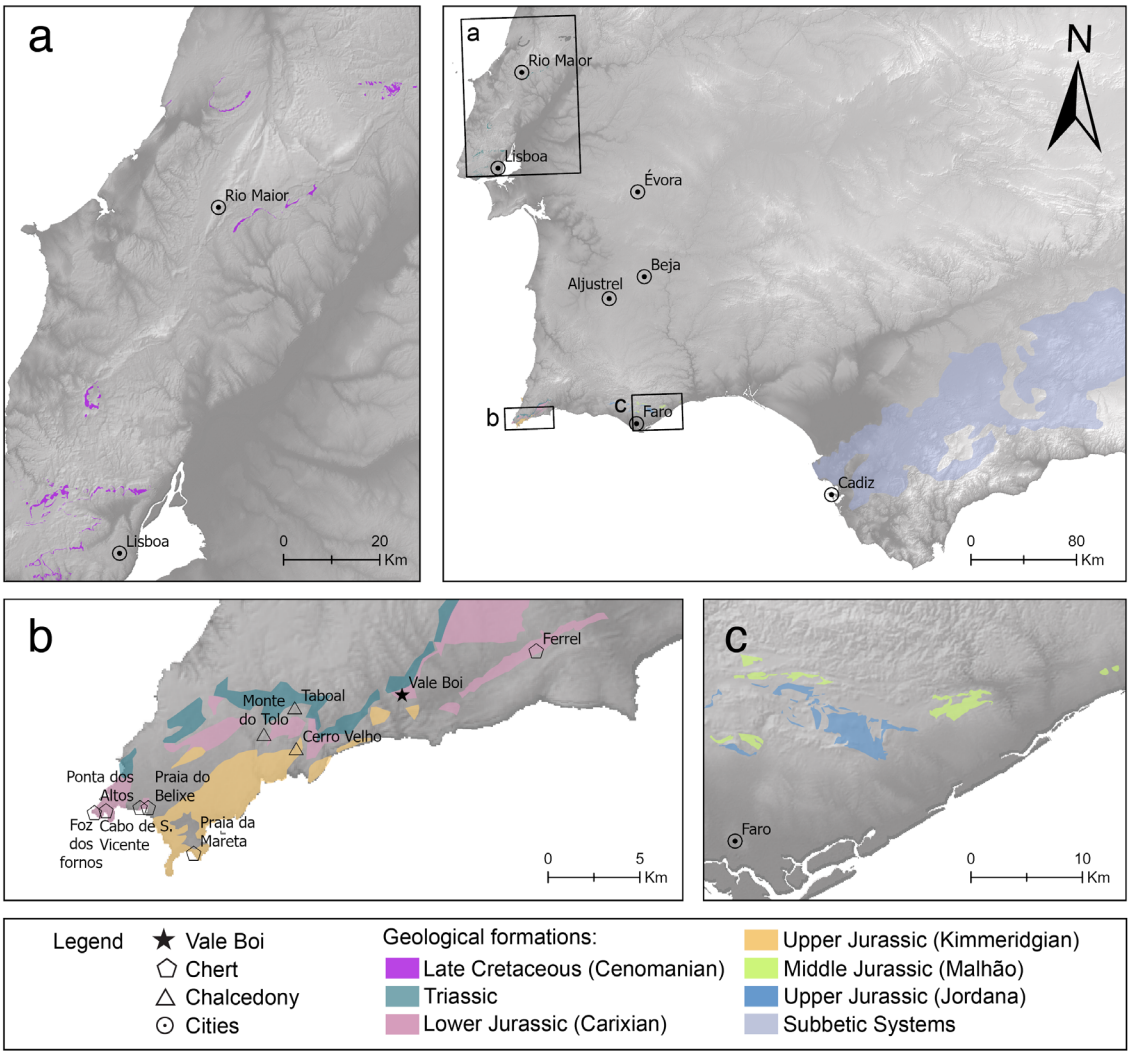

Figure 3.1. Iberian Peninsula map with locations and geological formations mentioned throughout the paper. a) Detail of the central Portugal region where the Cenomanian formations with chert nodules are located. b) Detail of southwestern Portugal, with chert and chalcedony bearing formations, outcrops, and location of Vale Boi. c) Detail of eastern Algarve with chert-bearing formations. The figure was produced using ArcGIS Pro 3.2.

3.1.2 Regional geological background

The Algarve region is a complex territory, marked by several geomorphic sub-regions and geological units that provide different lithological resources. Two of the main geological units which characterise the Algarve are: 1) the Baixo Alentejo Flyschoid Group, part of the south Portuguese Zone (Paulo Fernandes et al., 2012; Oliveira, 1984; Onézime et al., 2003), located in the north sector of the region, and characterised by

schists, greywackes and quartzites; and 2) the Algarve basin in the south, which is characterised by limestones, dolomites and marls (Terrinha et al., 2006). It is within these limestones and dolomitized limestones from the Triassic to the Upper Jurassic where chalcedony and chert nodules/beds can be found (Manuppella et al., 2007; Manuppella et al., 1987; Ribeiro, 2005; Rocha et al., 1983; Rocha et al., 1979; Terrinha et al., 2006).

The availability of regional resources containing cherts and the characterisation of their lithologies has already been published by our team (Belmiro et al., 2023), and we herein present the summarised main findings. The results showed the existence of abundant chert nodules and beds found in the Lower Jurassic (Carixian) formation and Upper Jurassic (Kimmeridgian) formation, mostly outcropping in the cliff and beach areas of westernmost Algarve, at ~20 km southwest from the site of Vale Boi, and with one single inland outcrop located ~8 km east from the site (Figure 3.1 b). The Lower Jurassic nodules and beds can be found in abundant outcrops, but also frequently in sub-primary or secondary deposition settings in proximity to the outcrops, possibly due to natural erosion. However, in the case of the inland outcrop of Ferrel, the outcrop is partially destroyed due to recent human action, and chert can be found scattered as chunks or larger nodules. The Upper Jurassic nodules can be found in sub-primary deposition and are easily accessible, or in secondary deposition. The cherts from the previously mentioned formations are frequently opaque with yellow, grey, purple or red colours, occasionally with bands or laminations, and frequently with visible sponge spicules. Although abundant, these chert nodules are frequently small (~4-10 cm in length), with the largest nodules being ~20 cm, and frequently characterised by high levels of dolomitization and fractures. Petrographically, they are composed mainly of microcrystalline quartz, with wackestone or packstone textures, small percentages of macrocrystalline quartz, fibrous chalcedony and allochems composed of oxides and poorly preserved bioclasts. When identifiable, the bioclasts are echinoderms, radiolarians, sponge spicules and bivalve shells. The Upper Jurassic cherts of Mareta show similar petrographic characteristics, but with abundant calcispheres which are not always apparent under the stereomicroscope.

Chert sources were also identified in two formations from the eastern area of the Algarve (Figure 3.1 c). The Middle Jurassic Malhão formation chert outcrops were identified at around 80-100 km east of the site and characterised by chert nodules with

similar macroscopic features to those found in western Algarve. Petrographically they are composed mainly of microcrystalline quartz and characterised by wackestone textures, while dolomite, chalcedony and macrocrystalline quartz are also present in small percentages (<10%). Allochems are iron oxides, and albeit poorly preserved, several bioclasts can be identified: sponge spicules, radiolarians, ostracods, echinoderms, calcispheres and possibly tentaculites. The Upper Jurassic Jordana formation chert outcrops were identified at around 90 km east of Vale Boi and characterised by chert nodules with significantly different macroscopic features to those of other formations, with frequently small sizes (~5 cm), difficult removal from the host rock and unidentified secondary deposits. Petrographically they are composed mostly of microcrystalline quartz, with wackestone to packstone textures, and small percentages of fibrous chalcedony and dolomite (<10%). They show frequent iron oxides and very frequent bioclasts, albeit often poorly preserved and unidentifiable; identified fossils are calcispheres, bivalve shells, sponge spicules, ostracods, echinoderms and gastropods.

Chalcedony can be found ~10 km west of Vale Boi (Figure 3.1 b), within the marl-carbonated Triassic formations as lenses or nodules and was formed through hydrothermal processes (Bicho et al., 2013). Previous studies also note the presence of chalcedony (with frequent presence of cortex) in the immediate vicinity of the site (Gibaja Bao and Ferreira Bicho, 2013; Pereira et al., 2016a). The chalcedony frequently has fractures and fissures and is characterised by a fibrous quartz structure, without inclusions or fossils.

3.2 Materials and methods

To characterise the siliceous raw materials used during the UP occupations at Vale Boi and to identify their geological sources, we focused on chalcedony and chert archaeological materials from the Terrace and Shelter areas. These two areas were chosen since both have detailed spatial information, well-defined chronological sequences, and previous studies providing lithic technology, faunal, and geoarchaeological data. For this, we focused on layers that spanned the UP occupations, characterised by good preservation, a significant number of lithic finds and with radiocarbon dating (as mentioned in section Site description).

In this study, the terms chert and chalcedony follow the definitions provided by Luedtke (1992). We use the term chert to refer to sedimentary rocks composed primarily of microcrystalline quartz, which includes other possible varieties such as jasper, agate, or chalcedony. The term chalcedony is used in its petrographic sense and refers to cherts with a fibrous quartz structure. Since this definition of chalcedony implies a destructive method which cannot be applied to all archaeological chalcedony samples, we use the term based on the confirmed correlation between the macroscopic appearance of chalcedony and its petrographic characteristics, obtained through geological and archaeological thin sections.

Chert was chosen for this study as it is one of the three main raw materials used at the archaeological site of Vale Boi alongside quartz and greywacke. Other raw materials such as chalcedony, dolerite, and schists have also been identified (Belmiro et al., 2021; Cascalheira, 2010; Pereira et al., 2016a).

Using the field database with all individually coordinated lithic artefacts (all pieces larger than ~2 cm) (Belmiro, 2020), we compared the incidence of chert and chalcedony in opposition to the remaining lithics of other raw materials. Figure 3.2 shows that for the selected levels of the Terrace area (Figure 3.2 a), chert represents only ~15-20% of the lithic assemblage, while in the Shelter area (Figure 3.2 b), chert represents ~35-50% of the lithic assemblage from the Solutrean layers A, B, and C. Based on previous lithic studies in the Terrace and Shelter areas, the remaining 80% of other raw materials are mostly composed of quartz and greywacke (Belmiro et al., 2021; Cascalheira, 2010; Marreiros, 2009).

Although systematic raw material research has not been conducted on these materials, according to the regional geological context, they have been interpreted as local and readily accessible in the vicinity of the site (Pereira et al., 2016a). Frequently, the quartz and greywacke assemblages include large amounts of shattered and unknapped chunks or slabs and have been interpreted in great part as functionally specialised in activities related to the fragmentation of bones in the case of quartz and greywacke (Cascalheira et al., 2017b), or in grease rendering in the case of quartz (Manne et al., 2012). Previous studies from the Terrace area have also shown that when removing shatter and chunks, the percentages of chert become much more representative when compared to greywacke and quartz (Belmiro et al., 2021; Belmiro, 2020). Based on this,

despite the smaller amounts of individually plotted chert artefacts in the field database, chert continues to be one of the main raw materials to produce lithic stone tools, with complete knapping sequences and formal toolkits. The importance of chalcedony can also be seen in its use to produce formal tool kits during specific technocomplexes at the site, such as a Vale Comprido point, the fossil-director for the Proto-Solutrean in western Portugal (Belmiro et al., 2021) or a laurel leaf preform in the Solutrean layers (Gibaja Bao and Ferreira Bicho, 2013).

We employed both macroscopic and petrographic methods to achieve a more comprehensive characterisation of the materials, aiming to offset the inherent limitations of each method (Luedtke, 1992).

Macroscopic analysis, while revealing several limitations related to the absence of quantitative variables (Bustillo et al., 2009), proved to be advantageous given the extensive sample size of chalcedony and chert lithics under examination (n=4458). The distinct features of various local cherts facilitate their differentiation from cherts of neighbouring origins. Consequently, a macroscopic approach offered a non-destructive, efficient, and cost-effective method for characterising all materials (Bustillo et al., 2009; Tarriño and Terradas, 2013). Therefore, we implemented an initial phase of macroscopic analysis, subsequently augmented by petrographic study to diminish the subjectivity of the analysis and enhance the material characterisation with petrographic data. The synergistic application of these two methods has been previously validated in the characterisation of Algarve region cherts, following recent geological survey efforts (Belmiro et al., 2023). Hence, an extensive macroscopic and petrographic collection was already available for comparative analysis with archaeological materials, employing consistent methodologies. This reference collection is the Lusolit lithotheque, hosted physically at ICArEHB (University of Algarve, Faro) and digitally at www.lusolit.icarehb.com, and aided in the characterisation and source attribution of cherts.

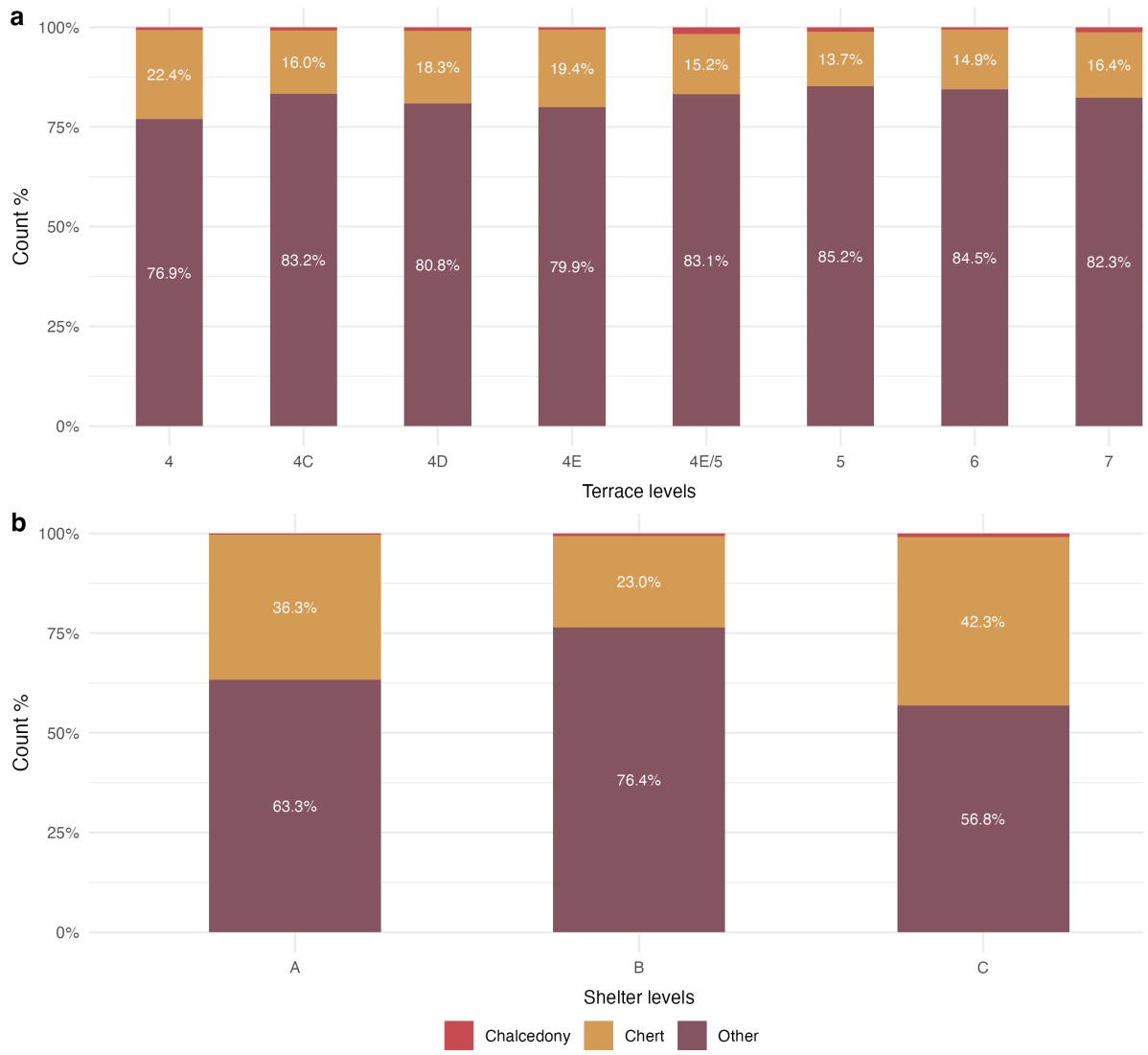

Figure 3.2. Comparison of chert, chalcedony, and other raw materials piece plotted in the Terrace (a) and Shelter (b) areas of Vale Boi.

Hand samples were used throughout the macroscopic characterisation for comparison with the archaeological materials, and the archaeological thin sections were compared with the previously studied geological chert thin sections. To identify the source of other lithologies which are not congruent with the regional cherts and identify possible long-distance chert procurement, we used hand samples and thin sections of cherts from central Portugal also available in the Lusolit lithotheque. The lithotheque from the Unit of Geoarchaeology and Archaeometry Applied to Historic Artistic and Monumental Heritage from the University of Cadiz (UCA) was also visited to understand the macroscopic variability of the local and regional cherts of the lower Guadalquivir

basin, within the Atlantic strip of southwestern Spain (present-day provinces of Huelva and Cádiz).

Following previous studies, we classify the distance of chert sources from the site as local (1-30 km from the site), regional (30-120 km), and long-distance (>120 km) (Herrero-Alonso et al., 2020; Tarriño et al., 2015).

The macroscopic analysis of the archaeological materials was divided into two steps. The first step included a preliminary characterisation using a hand lens of 10x magnification. This step allowed us to create types and subtypes based on similar macroscopic characteristics frequently acknowledged to be useful to describe and discern between different types of chert; these included characteristics such as colour, translucency, and feel (Luedtke, 1992)—the complete data dictionary for the recorded variables can be found in the Supplementary Information (Online Resource 1). In the second step, we used a Nikon SMZ25 stereomicroscope to observe each sample in further detail, which allowed us to better characterise the artefacts (especially regarding inclusions and alterations), and the previously established types—the data dictionary used for the individual samples can also be found in the Supplementary Information (Online Resource 1). Given the inherent macroscopic variability of the geological samples and archaeological specimens, as well as the number of samples, the database used for the individual analysis was simplified and focused on collecting data related to weight, cortex, and alterations. This first step was applied to a total of 4458 artefacts: a sample of 3627 chert artefacts from the UP sequence of the Terrace area (levels 7 to 4) and 831 chert artefacts from the Solutrean sequence of the Shelter area (layers A, B, C; all samples without an attributed layer on the database were excluded from the analysis).

While the advantages of employing a macroscopic methodology for analysing the cherts of Vale Boi are notable, a limitation of this approach is its inability to unequivocally characterise and categorise artefacts that exhibit surface alterations typical of an open-air site, including those related to fire, since weathered and altered surface may destroy visible structures and even alter the chemical composition (Delluniversità et al., 2019). Other studies frequently exclude samples that display intense fire damage or several surface alterations (Delluniversità et al., 2019; Gómez de Soler et al., 2020; Soto, 2016). For the present study, whenever artefacts displayed extensive alterations and could not be unequivocally characterised (Figure 3.3), and given the inexistence of a reference

collection for local altered cherts, they were analysed using the individual sample dataset (Online Resource 1) but grouped in a category of indeterminate cherts (INDET). This category included key alterations such as heat/fire-related alterations which clearly impacted the macroscopic characteristics of the samples, fully changing its colour, lustre and texture, and covering them in crazings (e.g., Figure 3.3 a). Similarly, it also included alteration rinds that extended through most of the sample, impeding the identification of its original colour, texture, translucency, inclusions and fossils (e.g., Figure 3.3 b) and the presence of extended pitting. However, whenever surface alterations were present in only a limited area of the sample leaving recognisable macroscopic features and fossils, or when key elements were distinguishable to make a characterisation (e.g., reddening in the Type 2 cherts, Online Resource 2, figure s5), the samples were not collapsed into the INDET category.

As seen in Table 3.1, level 4 shows the highest percentages of indeterminate artefacts, corresponding to ~40% of the total sample (n=1037). This is due to the frequent alterations of the artefacts, especially related to patinas and alteration rinds, pits, and fire/heat alterations. For all other levels in the Terrace, indeterminate represents on average ~28% of the chert artefacts, while in the Shelter the frequency of INDET is slightly lower (~20-25%).

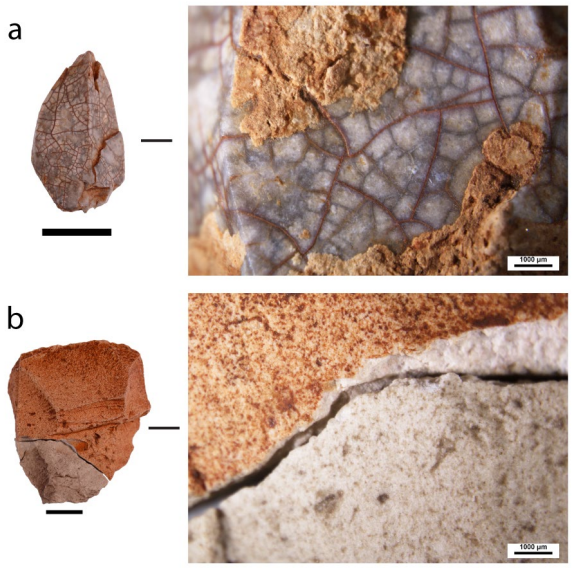

Figure 3.3. Samples with extensive alterations which prevented the identification of chert type. a) artefact with cracks, white patina and reddening covering 100% of the surface; b) artefact with surface alterations, displaying a portion with patina (brown) and a portion without patina (grey), cleaned with Hydrochloric acid.

As previously mentioned, the macroscopic study was followed by a petrographic approach. To better characterise the different chert types identified in the macroscopic analysis and aid in minimising the inherent caveats of macroscopic methods, 22 thin sections were prepared at the Thin Section Lab (Toul, France). The samples chosen for this analysis include at least one sample from each type present throughout the stratigraphy of the Terrace area, from different archaeological levels (Table 3.2). For types that showed high macroscopic variability (e.g., translucency and colour variation or differentiated bioclast facies), thin sections from sub-types were analysed to collect petrographic data that could reflect this variability. Petrographic thin sections were analysed by polarised light microscopy (Nikon LV100ND) to determine the mineral composition, textural characteristics, allochems, and bioclasts, as well as any other alterations.

The complete petrographic analysis for all thin sections studied in this paper (including macroscopic and microscopic figures) can be found at our online research compendium (https://doi.org/10.17605/OSF.IO/DBFT2). A detailed macroscopic and petrographic description and figures for each type and sub-type of chert and chalcedony (Online Resource 2) and the data dictionary used for the petrographic analysis (Online Resource 1) can be found in Supplementary Information. The complete set of images of the geological thin sections can also be consulted in the LusoLit online database.

The entirety of the R code used for the analysis, datasets, and visual representations contained in this paper can be accessed through our online research compendium. 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 under the MIT license, data under CC-0, and figures under CC-BY (additional details can be found in Marwick, 2017).

Table 3.1. Number and percentage of grouped and indeterminate (INDET) artefacts by level in the Terrace (levels 4 to 7) and Shelter (A to C) areas.

Group	4	4C	4D	4E	4E/5	5	6	7	A	B	C
Grouped	619 (59.7%)	287 (71.8%)	287 (66.8%)	332 (73.5%)	155 (73.1%)	211 (71%)	434 (73.1%)	149 (72.7%)	72 (72.7%)	212 (69.3%)	349 (81.9%)
Indeterminate	418 (40.3%)	113 (28.3%)	143 (33.3%)	120 (26.6%)	57 (26.9%)	86 (29%)	160 (26.9%)	56 (27.3%)	27 (27.3%)	94 (30.7%)	77 (18.1%)
Total	**1,037 (100%)**	**400 (100%)**	**430 (100%)**	**452 (100%)**	**212 (100%)**	**297 (100%)**	**594 (100%)**	**205 (100%)**	**99 (100%)**	**306 (100%)**	**426 (100%)**

Table 3.2. List of archaeological thin sections, with the summarised description of observed macroscopic variability and sub-types.

Type	Sample ID	Level	Macroscopic variability/sub-type description
Type 1	I19-1615	4D	-
Type 2	I19-2835	5	-
Type 2	H18-1938	4D	Type 2 sample with surface alterations.
Type 2	H21-3095	4C	Type 2 multi-coloured banding sub-type with concentration of bioclasts.
Type 2	H21-4234	5	Type 2 multi-coloured banding sub-type without concentration of bioclasts.
Type 2	H19-2426	4D	Type 2 sample with reddening and possible heat-related alterations.
Type 2	I19-2226	4E	Type 2 sample with large iron oxides and rare sponge spicules.
Type 3	I20-3160	5	-
Type 4	H20-2441	4E	-
Type 5	I21-3252	4E	-
Type 5	H18-2708	5	Type 5 banding sub-type.
Type 6	I19-3350	6	Type 6 sample with light white patination.
Type 6	I20-3689	6	-
Type 6	J18-778	5	Type 6 with thick white patination.
Type 6	I20-3951	6	Type 6 light brown with opaque white exterior sub-type.
Type 6	H19-4074	6	Type 6 with lamination and white broad mottling sub-type.
Type 7	L19-64	5	Type 7 with sponge spicule (01a) and peloidal (01b) facies.
Type 7	J18-1264	8	Type 7 with peloidal/oolitic (04) facies.
Type 8	H19-2924	4E	-
Type 9	I21-2966	4C	-
Type 10	H19-4216	6	-
INDET	H20-4166	6	Sample with thick white patination.

3.3 Results

3.3.1 Characterisation and source attribution

Through the macroscopic and petrographic analysis, we identified 10 main chert/chalcedony types, present throughout the stratigraphy in the Terrace and Shelter areas (a summarised characterisation table can be found in the Supplementary Information, Online Resource 3). A distinct type (Type 11) was identified exclusively in the Shelter area, with only a limited presence in the Terrace (n=2), and 16 varieties, each consisting of one to three samples, were identified across various levels of both the Terrace and Shelter. The latter were clustered into a category named Trace Lithotypes (TL). Through the comparison with the reference collections, we identified cherts congruent with the local sources and cherts that are likely not local due to significant

differences in appearance, fossil content, and petrography when compared to the cherts available in the geological setting located within a 30 km radius of Vale Boi. Table 3.3 shows the different types of identified cherts and possible sources whenever attribution was possible.

Table 3.3. Chert types identified during the analysis and potential sources. The distance column refers to the distance of the potential source from Vale Boi, as the crow flies. Only the TL samples with possible identified sources were included in the table.

Chert type	Potential source	Distance from source
Type 1	Triassic volcanic formations	<10 km
Type 2-5	Lower Carixian formations, southwestern Portugal	<20 km
Type 6	Upper Cretaceous formations, central Portugal	~215-250 km
Type 7	Betic Systems, southern Spain	~250 km
Type 8	-	-
Type 9	Betic Systems, southern Spain	~250 km
Type 10	-	-
Type 11	-	-
TL01	South Portuguese Zone, southern/central Portugal	>100 km
TL10-11	Upper Cretaceous formations, central Portugal	~215-250 km
TL15-16	Betic Systems, southern Spain	~250 km

3.3.1.1 Cherts congruent with local sources (Types 1-5)

The raw materials which are congruent with local sources are the chalcedony and massive, micro-cryptocrystalline cherts (Figure 3.4). The chalcedony (Type 1; Figure 3.4 a) is identified as a massive, fibrous variety without allochems (Figure 3.4 a2). It represents 6.6% of the overall Terrace cherts (excluding INDET) and 2.6% in the Shelter. It presents a colourless and translucent appearance, frequently exhibiting partial or complete white patination (Figure 3.4 a1). This type is marked by extensive crystallisations, irregularities, and fractures, coupled with post-depositional alterations that challenge the identification and preservation of the cortex. Both macroscopic and petrographic analyses confirm its congruence with hydrothermal chalcedony located

within lenses in Triassic volcanic formations, in the known outcrops of Monte do Tolo, Taboal and Cerro Velho (<10 km west of Vale Boi, as the crow flies; Figure 3.1 b), which are similarly marked by irregularities and fractures.

The cherts are massive micro-cryptocrystalline quartz from a marine environment (Figure 3.4 b-h). They represent ~60% of the overall Terrace cherts and ~80% of the chert in the Shelter. Macroscopically, these types show variability which resulted in their separation in four different macroscopic types (Type 2 to 5). In general, these are opaque to sub-translucent cherts, with colours varying from brown, yellow, pale red, and grey, with the frequent presence of spicules and iron oxides. The differences are in their colours, nodule morphology, frequency, and variety of bioclasts (Type 2 including triaxon sponge spicules and echinoderm spines), something already identified in the geological samples (Belmiro et al., 2023). As seen in Table 3.4, whenever present, the cortex seems to show a mixture of irregular cortex and rounded cortex, both from an outcrop source. Petrographically, however, these cherts are homogeneous, except for a small number of artefacts with a banded variety within Type 5. These cherts are characterised by wackestone textures, with accessory amounts of macrocrystalline quartz and fibrous chalcedony, frequently found replacing fossils and occasionally dolomite. Type 5 shows higher percentages of micrite/sparite. In all samples, fossils range from common to very frequent, albeit frequently unidentifiable. When identifiable in thin section, they are sponge spicules (Figure 3.4 b2, c2, h2), with the rare occurrence of possible foraminifera (Type 2 and Type 5) and ostracod (Figure 3.4 h3) in a sample from Type 5. Porosity varies between 10% and 1%, of vug type. Despite the petrographic homogeneity between local types, this macroscopic separation was maintained for its possible usefulness in identifying preferred types of nodules or macroscopic varieties through time and for future correlation with technological data.

Table 3.4. Frequency of cortex type and thickness by raw material from the Terrace area, characterised during the individual analysis of the lithic assemblage.

Variable	TYPE 1, N = 8	TYPE 2, N = 267	TYPE 3, N = 138	TYPE 4, N = 112	TYPE 5, N = 134	TYPE 6, N = 163	TYPE 7, N = 108	TYPE 8, N = 19	TYPE 9, N = 18	TYPE 10, N = 3	TL, N = 3
Cortex type											
Irregular	1 (13%)	74 (28%)	52 (38%)	50 (45%)	31 (23%)	20 (12%)	30 (28%)	2 (11%)	0 (0%)	0 (0%)	0 (0%)
Rounded	1 (13%)	118 (44%)	53 (38%)	35 (31%)	69 (51%)	116 (71%)	46 (43%)	14 (74%)	14 (78%)	1 (33%)	3 (100%)
Pebble	0 (0%)	4 (1.5%)	2 (1.4%)	0 (0%)	2 (1.5%)	6 (3.7%)	1 (0.9%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Indeterminate	6 (75%)	71 (27%)	31 (22%)	27 (24%)	32 (24%)	21 (13%)	31 (29%)	3 (16%)	4 (22%)	2 (67%)	0 (0%)
Thickness											
Thin	7 (88%)	121 (45%)	49 (36%)	24 (21%)	105 (78%)	151 (93%)	37 (34%)	13 (68%)	13 (72%)	0 (0%)	3 (100%)
Medium	1 (13%)	122 (46%)	77 (56%)	53 (47%)	23 (17%)	10 (6.1%)	51 (47%)	5 (26%)	3 (17%)	3 (100%)	0 (0%)
Thick	0 (0%)	24 (9.0%)	12 (8.7%)	35 (31%)	6 (4.5%)	2 (1.2%)	20 (19%)	1 (5.3%)	2 (11%)	0 (0%)	0 (0%)

Based on the previously described macroscopic and petrographic characteristics of the Lower Jurassic cherts of the Algarve (Belmiro et al., 2023), we interpret Types 2, 3, 4, and 5 to be local, as they are congruent with the described characteristics representative of cherts from the Lower Jurassic found in the known outcrops Cabo S. Vicente, Foz dos Fornos, Ponta dos Altos, Praia do Belixe and Ferrel (Carixian; <20 km from Vale Boi, as the crow flies), possibly Upper Jurassic Kimmeridgian outcrops of Mareta (~15 km from Vale Boi, as the crow flies) and Middle Jurassic Malhão formations (80-100 km east of Vale Boi, as the crow flies) of the Algarve basin. Types 2 and 3 are congruent with the frequently available brown/yellow and red nodules and beds (Figure 3.4 b-d), ranging from uncommon to very frequent fossils. These can be found in all previously mentioned outcrops. The macroscopic similarities of Types 4 and 5 are more limited (Figure 3.4 e-h), as they show similarities to specific nodules, rarely found in the known outcrops, and mostly located in the inland Lower Jurassic outcrop of Ferrel (Figure 3.1 b). As such, we interpret these cherts as local, but possibly from nodules and inland outcrops that are no longer frequently available or visible in the landscape. This is especially relevant since the inland outcrops of Ferrel are currently mostly destroyed and can be found in poor preservation conditions, due to recent human intervention and construction work, and with small, broken nodules in the surface, frequently altered (Belmiro et al., 2023).

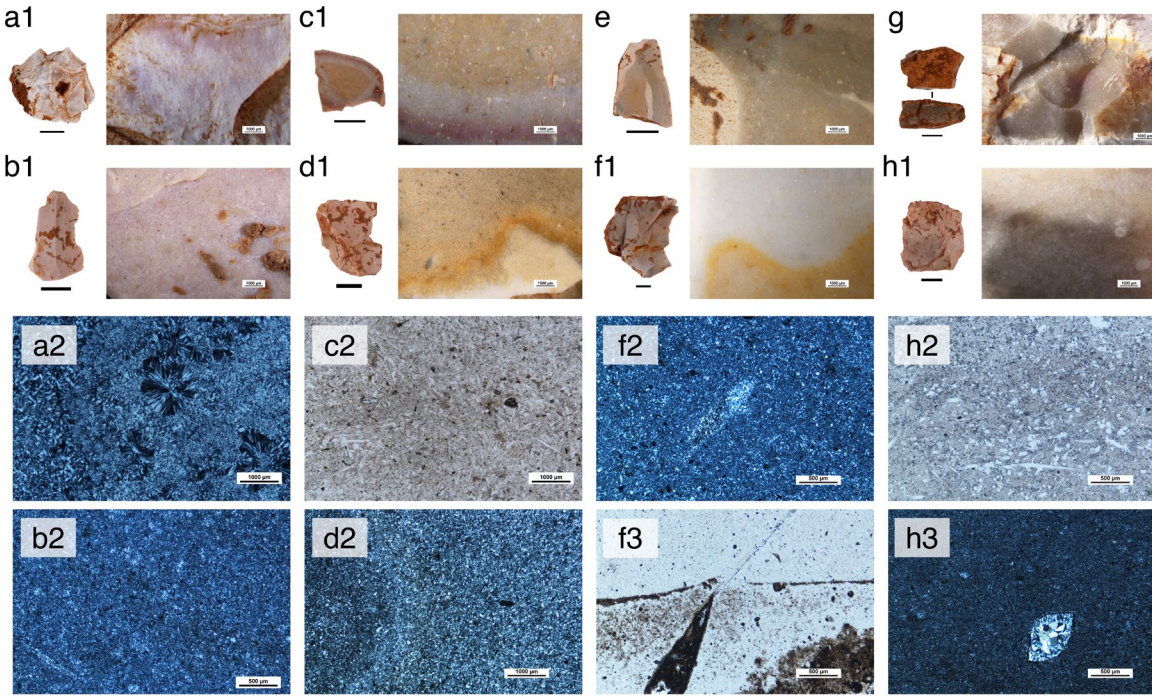

Figure 3.4. Variability of local chert types and main petrographic characteristics. a) Type 1 macroscopic and microscopic views: a1) macroscopic view with a stereomicroscope of white patina and fractures; a2) microscopic view of thin section (XPL), with visible fibrous chalcedony composition and without allochems. b) Type 3 macroscopic and microscopic views: b1) macroscopic view with a stereomicroscope of iron oxides and unidentifiable fossils; b2) microscopic view of thin section (XPL), with visible unidentifiable fossils and iron oxides. c-d) Type 2 macroscopic and microscopic views of multicoloured (c) and single-colour (d) varieties. c1) macroscopic view with a stereomicroscope of the multicoloured bands with iron oxides and unidentifiable fossils; d1) macroscopic view with a stereomicroscope of iron oxides and unidentifiable fossils; c2) microscopic view of thin section (PPL), with visible unidentifiable fossils, sponge spicules and iron oxides; d2) microscopic view of thin section (XPL), with visible unidentifiable fossils and iron oxides. e-f) Type 4 macroscopic and microscopic views: e) macroscopic view with a stereomicroscope of unidentifiable fossils and white splotches; f1) macroscopic view with a stereomicroscope of iron oxides and unidentifiable fossils within white and yellow splotches; f2) microscopic view of thin section (XPL), with visible unidentifiable fossils and iron oxides; f3) microscopic view of thin section (PPL) with a concentration of fossils (possibly sponge spicules) and a fracture. g-h) Type 5 macroscopic and microscopic views: g) macroscopic view with a stereomicroscope; h1) macroscopic view with a stereomicroscope with visible unidentifiable fossils; h2) microscopic view of thin section (PPL), with visible unidentifiable fossils, sponge spicules and iron oxides; h3) microscopic view of thin section (XPL) with small unidentifiable fossils, iron oxides and a possible ostracod replaced by fibrous chalcedony and macrocrystalline quartz.

3.3.1.2 Cherts not congruent with local sources (Types 6-11 and TL)

We identified six chert types with macroscopic and petrographic characteristics that are not congruent with the chert available in known outcrops in western Algarve (Figure 3.5).

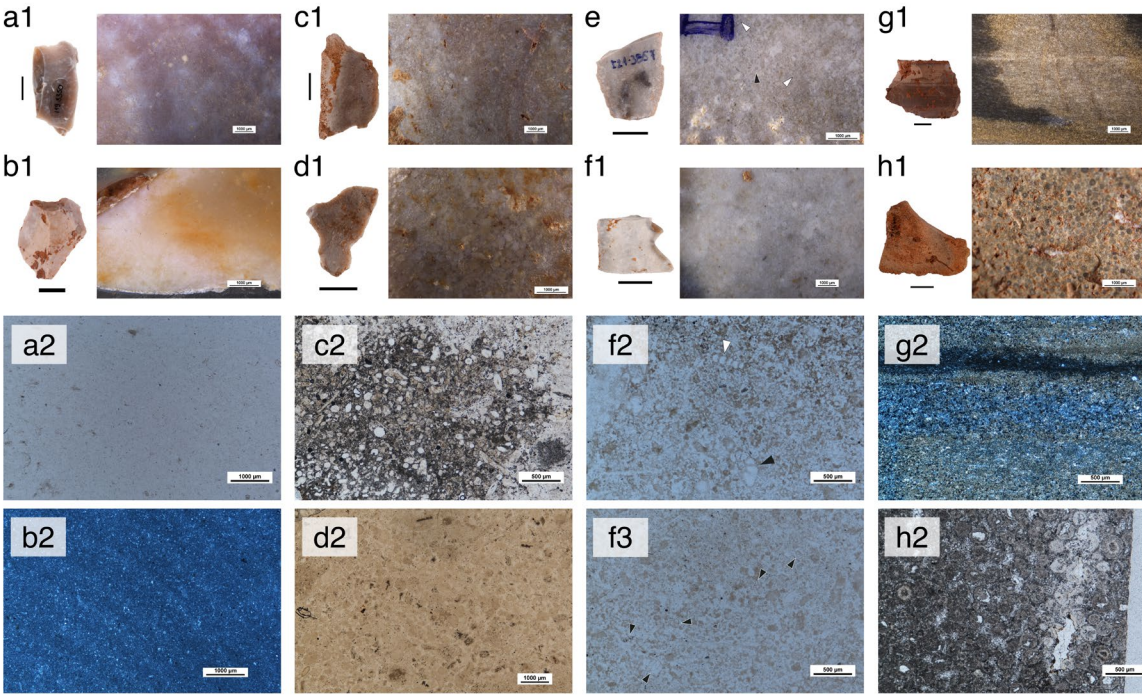

Figure 3.5. Variability of non-local types and main petrographic characteristics. a-b) Type 6 macroscopic and microscopic views: a1) macroscopic view with a stereomicroscope with a small degree of white patina and no visible fossils; b1) macroscopic view with a stereomicroscope of a thick alteration rind but translucent interior where some unidentifiable fossils are visible; a2) microscopic view of thin section (PPL) with a mudstone texture; b2) microscopic of thin section (XPL) with small unidentifiable fossils and a laminar microstructure. c-d) Type 7 macroscopic and microscopic views of the peloidal facies (c) and oolitic facies (d): c1) macroscopic view with a stereomicroscope of peloids and sponge spicules; d1) macroscopic view with a stereomicroscope of poorly preserved ooids; c2) microscopic view of thin section (PPL) with packstone texture composed mainly of peloids; d2) microscopic view of thin section (PPL) with packstone texture composed mainly of ooids. e-f) Type 8 macroscopic and microscopic views, with foraminifera represented by the white and black arrows: e) macroscopic view with a stereomicroscope with abundant unidentifiable fossils and foraminifera; f1) macroscopic view with a stereomicroscope with abundant unidentifiable fossils but no visible foraminifera; f2) microscopic view of thin section (PPL) with packstone texture composed of unidentifiable fossils and foraminifera which are not visible macroscopically; f3) microscopic view of thin section (PPL) with packstone texture composed of unidentifiable fossils and foraminifera which not are visible macroscopically. g) Type 9 macroscopic and microscopic views: g1) macroscopic view with a stereomicroscope of unidentifiable fossils and two different fabrics; g2) microscopic view of thin section (XPL) with packstone texture composed of concentrations of unidentifiable fossils and opaques which create a banded microstructure. h) Type 10 macroscopic and microscopic views: h1) macroscopic view with a stereomicroscope of ooids and fractures filled with chalcedony; h2) microscopic view of thin section (PPL) with packstone texture composed of ooids with different levels of preservation.

Type 6 (Figure 3.5 a-b) corresponds to a massive cryptocrystalline quartz with a mudstone texture, from a marine environment. It represents ~18% of the overall Terrace cherts and ~12% of the chert in the Shelter. This chert is translucent and shows a variety of colours, ranging from brown, red, and grey, which seem to vary in function of the artefact's thickness. In unaltered samples, visible bioclasts are rare. The cortex is mostly rounded, and rarely pebble-like, ranging from thin to medium thickness (Table 3.4). Two sub-types were individualised based on macroscopic characteristics such as colour, translucency variation, and patterns, although they may simply reflect the use of specific nodules from within Type 6's variability. Five thin sections were produced to better characterise the macroscopic variability of this type and sub-types. The petrographic analysis shows the samples are characterised by a massive microstructure, mainly composed of cryptocrystalline quartz (between 95-97% in the samples), with accessory fibrous chalcedony found replacing fossils or filling fractures (Figure 3.5 a2-b2), and in some samples macrocrystalline quartz, microcrystalline quartz, and micrite/sparite. Allochems are opaques, iron oxides, and bioclasts. Bioclasts are unidentifiable and poorly preserved, with rare identifiable fossils such as sponge spicules, replaced by fibrous chalcedony and rarely by microcrystalline quartz. Porosity is present between <1-1%, of vug type when identifiable.

The similarities between chert artefacts at the UP occupations of Vale Boi and the chert from the Rio Maior region (central Portugal; Figure 3.1 a) have been previously suggested although without systematic studies to ascertain the attribution (Bicho et al., 2013; Pereira et al., 2016a). These Cretaceous cherts, mostly found in secondary deposition settings, are described as frequently translucent, with geodes, colours ranging from yellow to red or grey, and mineralogically homogeneous between them. Petrographic studies from central Portugal highlight the presence of iron oxide accumulations and rare fossil ghosts or frequently difficult to see in thin section (Matias, 2016). When identified, sponge spicules and possible rare foraminifera have been identified (Matias, 2012).

Studies of Upper Cretaceous cherts located in the Lisbon area describe cherts with similar macroscopic characteristics (Figure 3.1 a), with micro-cryptocrystalline quartz mudstones with bioclasts such as sponge spicules or bivalve fragments, or wackestone/packstone textures with abundant bioclasts, including ostracods and

different types of foraminifers (Jordão and Pimentel, 2022). These cherts have also been reported as found in highly variable cobble morphologies and macroscopic traits, which is also observable through the reference samples from central Portugal hosted at LusoLit. Similar to the archaeological thin sections from Type 6 and congruent with other studies (Jordão and Pimentel, 2022; Matias, 2016), the thin sections produced from the Cretaceous cherts hosted at Lusolit show a massive, cryptocrystalline mudstone structure, with uncommon fossils (ghosts), iron oxides and low porosity (<1%). From these Cretaceous cherts from central Portugal, only the dark grey nodules (sample RT231, with petrographic descriptions available in our online research compendium) showed identifiable fossils which were rare ostracods.

Based on the macroscopic and petrographic similarities to the geological references from central Portugal and congruence with previous studies from this area, we interpreted Type 6 (and sub-types) as belonging to the macroscopically variable Cretaceous cherts (Upper Cenomanian formations) from central Portugal, between ~215-250 km (as the crow flies) north of Vale Boi (Figure 3.1 a).

Type 7 (Figure 3.5 c-d) is a massive micro-cryptocrystalline, peloidal/oolitic packstone, from a marine environment and possibly a high-energy, shallow depositional environment, due to the type, sorting, and preservation conditions of the ooids. In the terrace, it represents 10% of the overall Terrace cherts and less than 1% of the chert in the Shelter. It is characterised by white and grey colours. The cortex is from an outcrop, rounded and in lesser frequencies (<30%) irregular, and varying between medium thickness to thick (Table 3.4). This type shows several facies, with different types and concentrations of allochems and bioclasts, such as peloids (Figure 3.5 c1), ooids (Figure 3.5 d1), and sponge spicules. A detailed scheme of the facies can be found in the Supplementary Information (Online Resource 2). The petrography results show this chert has a massive microstructure and packstone texture (Figure 3.5 c2-d2). It is composed mainly of micro-cryptocrystalline quartz (80%), fibrous chalcedony (10%), and micrite (10%). Allochems are opaques, iron oxides, ooids, and peloids. The ooids are poorly preserved and only uncommonly show concentric lamellae in plane-polarized light. Unlike macroscopical observations, bioclasts under the thin section are all unidentifiable, although rare fossils may be bivalve shells. Porosity is variable (<1-10%).

The consultation of the lithotheque hosted at UCA allowed us to identify a subset of cherts with similarities to those from Type 7 from the Middle Subbetic region (Betic Systems, south Spain, Figure 3.1). These cherts are massive, sub-translucent, peloidal/oolitic packstones. Allochems include very frequent peloids and ooids. The peloids are densely arranged in the samples, more or less visible depending on the alterations to the surface or the thickness. The ooids are poorly sorted, with oval or round shapes, and replaced by quartz. Uncommonly the ooids show a preserved nucleus. The presence of bioclasts varies between samples, ranging between common to rare, and when present/identifiable include sponge spicules (common), foraminifera (rare to uncommon), and echinoderm spines (rare). Similar cherts have also been identified and described in previous works, describing grey cherts with peloidal and oolitic facies and occasional foraminifera (Rodríguez et al., 2011). Despite the non-existence of thin sections for comparison, the macroscopic similarities between the cherts allow us to interpret Type 7 as coming from the Upper Jurassic formations of the Betic Systems, located in the south and southeastern Iberian Peninsula, at least 250 km (as the crow flies) east from Vale Boi (Figure 3.1).

Type 8 (Figure 3.5, e-f) corresponds to a massive micro-cryptocrystalline quartz from a marine environment and shelf/platform depositional environment. It represents ~2% of the overall Terrace cherts and ~5% of the chert in the Shelter. Identified and well-preserved fossils are foraminifera from the Pfenderenidae family (Figure 3.5 e, f2), which are larger benthic foraminifera from marine environments (BouDagher-Fadel, 2008). The association of these foraminifera indicates this chert formed from sediments deposited possibly between the Jurassic to the Cretaceous. Macroscopically, this type is characterised by grey and white colours (Figure 3.5 e-f1). The translucency ranges from sub-translucent to opaque. Whenever present, the cortex is rounded and thin (Table 3.4). Petrographically, this type is a packstone (mudstone texture close to the edges) with a massive microstructure. It is composed of 97% micro-cryptocrystalline quartz, macrocrystalline quartz, and fibrous chalcedony mostly replacing fossils. Other minerals include uncommon iron oxides and the porosity is of vug type (3%). Fossil content is very frequent (Figure 3.5 f2-f3), albeit mostly unidentifiable and poorly preserved. Identified fossils are rare sponge spicules, rare ostracods with some degree of preservation, common small, unidentified foraminifera (100 μm) of differing preservation degrees, and

as mentioned above, foraminifera from the Pfenderenidae family (500 µm). Despite the macroscopic similarities between type 8 and cherts from the Middle Subbetic region chert formations (Figure 3.1), the geological reference samples showed no macroscopically visible foraminifera. However, our results indicate that despite no foraminifera being visible macroscopically, they are present in thin section. The fact that no foraminifera were identified in the small number of analysed samples from the UCA lithotheque with similarities to Type 8 (n=3) may simply reflect their uncommon visibility, possibly due to patination. Another possible source for Type 8 cherts may be the Upper Cretaceous wackestone/packstone cherts with foraminifers from the Lisbon region (Jordão and Pimentel, 2022). However, these studies do not specify the existence of Pfenderenidae foraminifers. Given the lack of this specific fossil in the reference samples from the Betic chert ~250 km east and southeast, and the central Portugal cherts 215-250 km north, the probable source of Type 8 remains unknown.

Type 9 (Figure 3.5 g) corresponds to a banded micro-cryptocrystalline quartz/micrite peloidal packstone. It corresponds to less than ~2% of the overall cherts in the Terrace and Shelter areas. It is opaque, has a heterogeneous structure and is characterised by a variable colour distribution: it shows a horizontal, finely laminated pattern, with dark grey bands intercalated with light grey bands (Figure 3.5 g1). Whenever present, the cortex is rounded and is generally thin (Table 3.4). In specific samples, the cortex is present on two parallel planes of the sample (parallel to the laminations), which indicates the chert was originally available in bedded layers. Petrographically this chert is a banded packstone (banding of sedimentary origin; Figure 3.5 g2), composed mostly of micro-cryptocrystalline quartz (48%), micrite (40%), dolomite (10%), and accessory fibrous chalcedony and mica (muscovite). The allochems are peloids, unidentifiable bioclasts, iron oxides, and opaque minerals. Porosity is low (1%). Although its origin is unknown, when visiting the UCA lithotheque, we identified a small type of banded black cherts without noticeable fossils or inclusions. Despite the lack of comparative petrographic data, the macroscopic resemblances raise the possibility that Type 9 belongs to Betic chert formations in southern Spain, 250 km east (as the crow flies) from the site (Figure 3.1).

Type 10 (Figure 3.5 h) is an oolitic packstone, massive micro-cryptocrystalline micrite/quartz from a marine environment and possibly a high-energy, shallow

depositional environment, due to the type, sorting, and preservation conditions of the ooids. It represents ~1% of the overall Terrace cherts and less than 0.1% of the chert in the Shelter. Its heterogeneous structure has two types of fabrics with different macroscopic characteristics: brown (opaque) and black (sub-translucent) fabric (Figure 3.5 h1). The sample chosen for the thin section is composed of 35% micro-cryptocrystalline quartz, 53% micrite, 9% macrocrystalline quartz, and accessory fibrous chalcedony (filling fractures) and mica; the percentages of quartz and micrite might be related to the fabrics present in the artefacts. Allochems are common iron oxides and very frequent ooids. Bioclasts are rare, poorly preserved, and replaced by quartz. The porosity is intraparticle and vug (10%). The ooids are distributed homogeneously across the sample (although macroscopically visible in the brown fabric) and are highly abundant and concentrated. They are poorly sorted, varying between 500 and 20 μm (Figure 3.5 h2), show round-to-elliptical shapes and their preservation is variable: some ooids show a poorly preserved micritic structure, while others show concentric laminae structures around a round nucleus (Flügel, 2010). This chert shows no similarities to any consulted reference material. Despite the existence of oolitic limestones in the Algarve region correspondent to Middle and Upper Jurassic formations and often described as whiteish (Rocha et al., 1979), the presence of oolitic chert in the region is not recognised in geological and archaeological literature (Cardoso et al., 2018; Rocha et al., 1979; Verissimo, 2004) and the visit of outcrops mentioned in the geological cartography did not allow their identification.

Type 11 (Figure 3.6) is a banded/laminated mudstone, characterised by the presence of a conchoidal fracture (within the nodule) and a non-conchoidal, laminar fracture (at the edges of the nodule). This chert type is grey, opaque, and without identifiable allochems. This chert shows a limited presence at the archaeological site as previously mentioned, restricted to the Solutrean occupations, and corresponding to less than 0.1% of the Terrace cherts and ~2% of Shelter cherts.

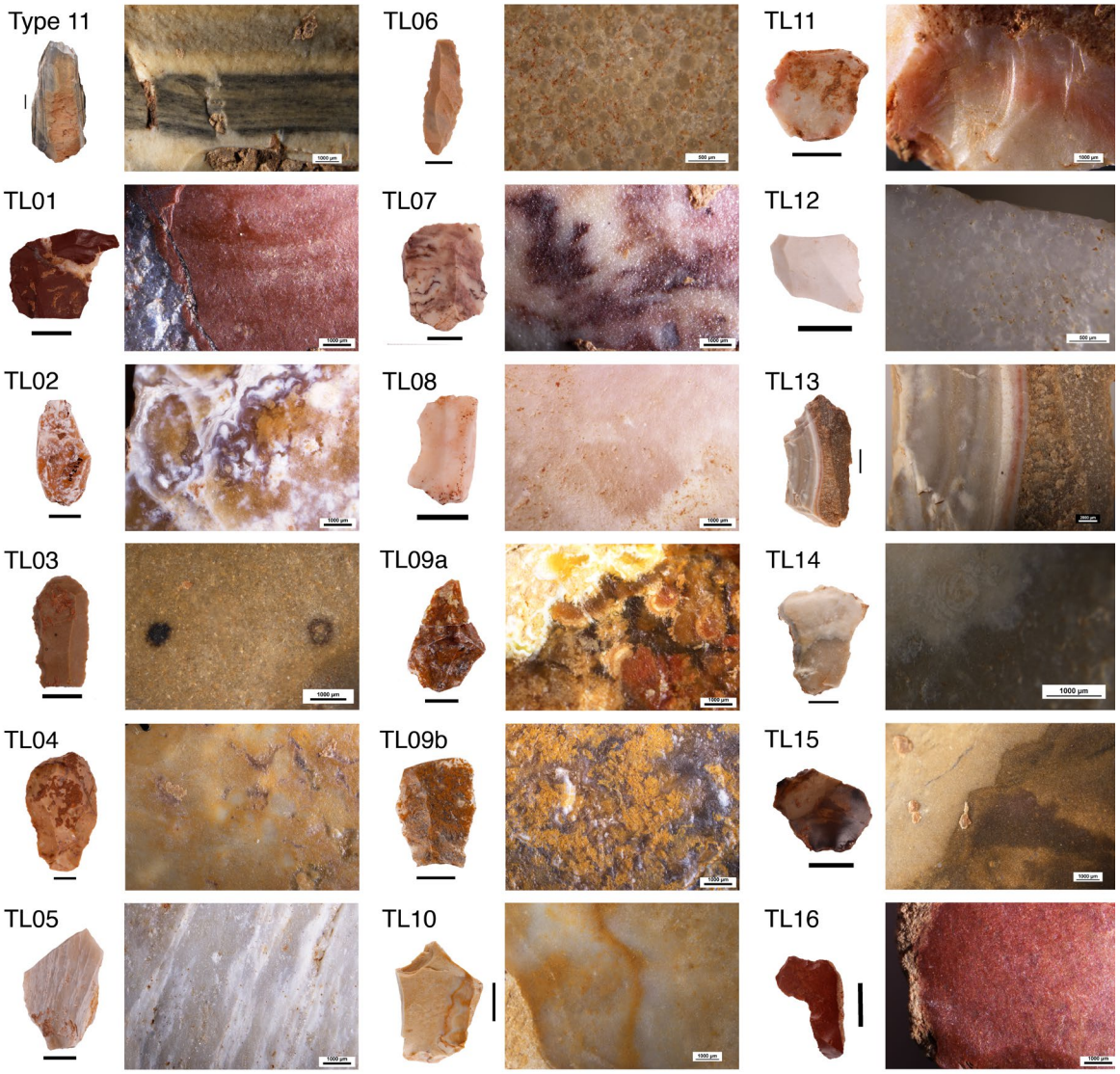

Figure 3.6. Macroscopic view with a stereomicroscope of non-local Type 11 and TL cherts. Type 11 – detail of banded patterns composed of parallel different fabrics; TL01 – detail of the jasper and fractures filled with chalcedony; TL02 – detail of the chalcedony with unidentified orange inclusions; TL03 – detail of two round inclusions, possibly iron oxides; TL04 - detail of massive chert with fractures filled with chalcedony; TL05 – detail of the banded pattern within the grey mudstone texture; TL06 - detail of the small, finely sorted ooids; TL07 – detail of the dendritic laminations, possibly composed of iron oxides; TL08 – detail of the mudstone structure, without the presence of allochems; TL09a/b – detail of the mossy, orange and red inclusions within the chalcedony; TL10 – detail of the speckling and laminated patterns within the mudstone structure; TL11 – detail of the banding within the mudstone structure; TL12 – detail of the poorly preserved ooids, only visible under the stereomicroscope; TL13 – detail of the bands and laminations within the mudstone texture fabric; TL14 – detail of an unidentified benthic foraminifera; TL15 – detail of the interface between the massive brown fabric and splotches; TL16 - detail of the of the massive structure with unidentifiable inclusions.

Finally, the TL types (Figure 3.6) are characterised by several samples without macroscopic correspondence to the previously identified types or to the local cherts and chalcedony from the Algarve region previously described by Belmiro et al. (2023). These are composed mostly of blanks or retouched tools, rarely with cortex (Table 3.4), and rarely the same TL type is found in different archaeological layers. A detailed description of these types can be found in the Supplementary Information (Online Resource 2). In both areas, the TL cherts compose less than 1% of the cherts.

Apart from the types common throughout the stratigraphy of the Terrace and Shelter, Type 11 and samples from the TL type also show no identifiable source. The exceptions are TL01, TL10-11 and TL15-16.

Jasper is known in the South Portuguese Zone area (Oliveira, 1984), from southern/central Portugal to Spain, north of the Algarve (from Aljustrel to Beja; Figure 3.1), suggesting that the source of TL01 may be from south/central Portugal at a minimum distance of 100 km north and northeast from Vale Boi (as the crow flies).

Similarly, despite being different from the most frequent Cretaceous nodules, the macroscopic similarities between TL10 and TL11 and specific nodules from central Portugal in the Lusolit lithotheque may indicate these cherts are from the Estremadura/Lisbon area (Figure 3.1 a). This difference in appearance may be due to the already-mentioned variability of the nodule's macroscopic characteristics.

Finally, TL15 and TL16 show macroscopic similarities to radiolarite reference samples located at the Cadiz lithotheque, which may indicate the source of these cherts is from the Middle Subbetic region (Domínguez Bella, 2010; Domínguez-Bella, 2006).

3.3.2 Stratigraphical distribution

3.3.2.1 Terrace area

Most chert types described above are consistently present across the Terrace stratigraphy (except for Type 11 which appears only in level 4 and in a small number of artefacts; n=2). However, being ubiquitous, we identified a difference in the percentages of chert types throughout the stratigraphy (Figure 3.7).

In the Gravettian occupations (levels 6 and 7) and at the start of the Proto-Solutrean (level 5) local cherts make up ~45-60%, while the combined non-local cherts make up ~65-40%. Level 6 shows the highest percentages of all non-local chert use, with specific types like Type 6 representing ~30%, although when considering the sum of weight, the percentages reduce, and non-local chert represents ~50% of total chert. The percentages of local chert increase in the following occupations. In the Proto-Solutrean (levels 4E and 4E/5) and Solutrean (levels 4, 4C, and 4D) local cherts make up more than ~70% of the sample and 80% when considering the sum of weight, while non-local cherts decrease significantly and represent percentages lower than 30%. Despite the increase of local cherts during the Proto-Solutrean and Solutrean, there are still significant differences between the local types present in the two technocomplexes. During the top Proto-Solutrean occupations the grey/white cherts (Type 4) are the most present chert with percentages between 35-20%, while in the Solutrean levels, the yellow/brown cherts (Type 2) are present in the highest percentage, at ~30%.

When plotting the weight, it is apparent that most of the samples are located under the 10 gr mark, with median and bottom quartiles often falling under the 5 gr line (Figure 3.8). Local types, such as Type 2, Type 4, and Type 5, although mostly represented by artefacts with a medium mass (~5-10 gr), show the heaviest and highest number of heavy artefacts. In comparison, other types, although showing some variation in the weight of artefacts, show smaller artefacts and their means and medians are frequently closer to the bottom quartile. As seen in (Figure 3.8), non-local types show larger weights from level 5 to level 7.

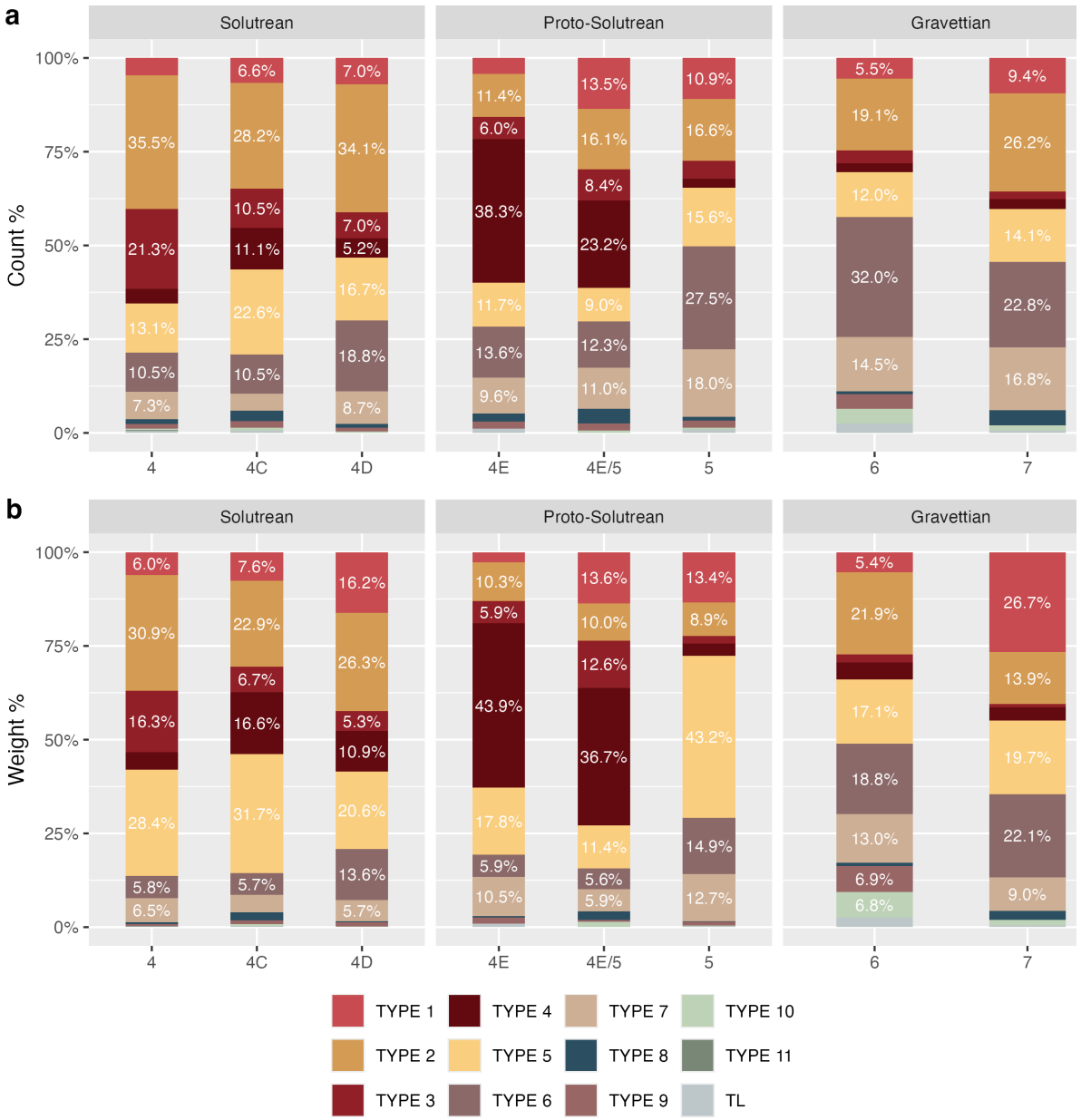

Figure 3.7. Terrace area chalcedony and chert type frequency (a) and weight sum (b) per level, without unidentifiable samples. Only percentages superior to the 5% threshold are shown in the figure. Type 1 to 5 (yellow and red colours) represent local chalcedony and cherts. Type 6, 7 and 9 represent non-local cherts with identified probable provenience (brown colours). Type 8, 10 and 11 represent non-local cherts with non-identified provenience (blue and green colours).

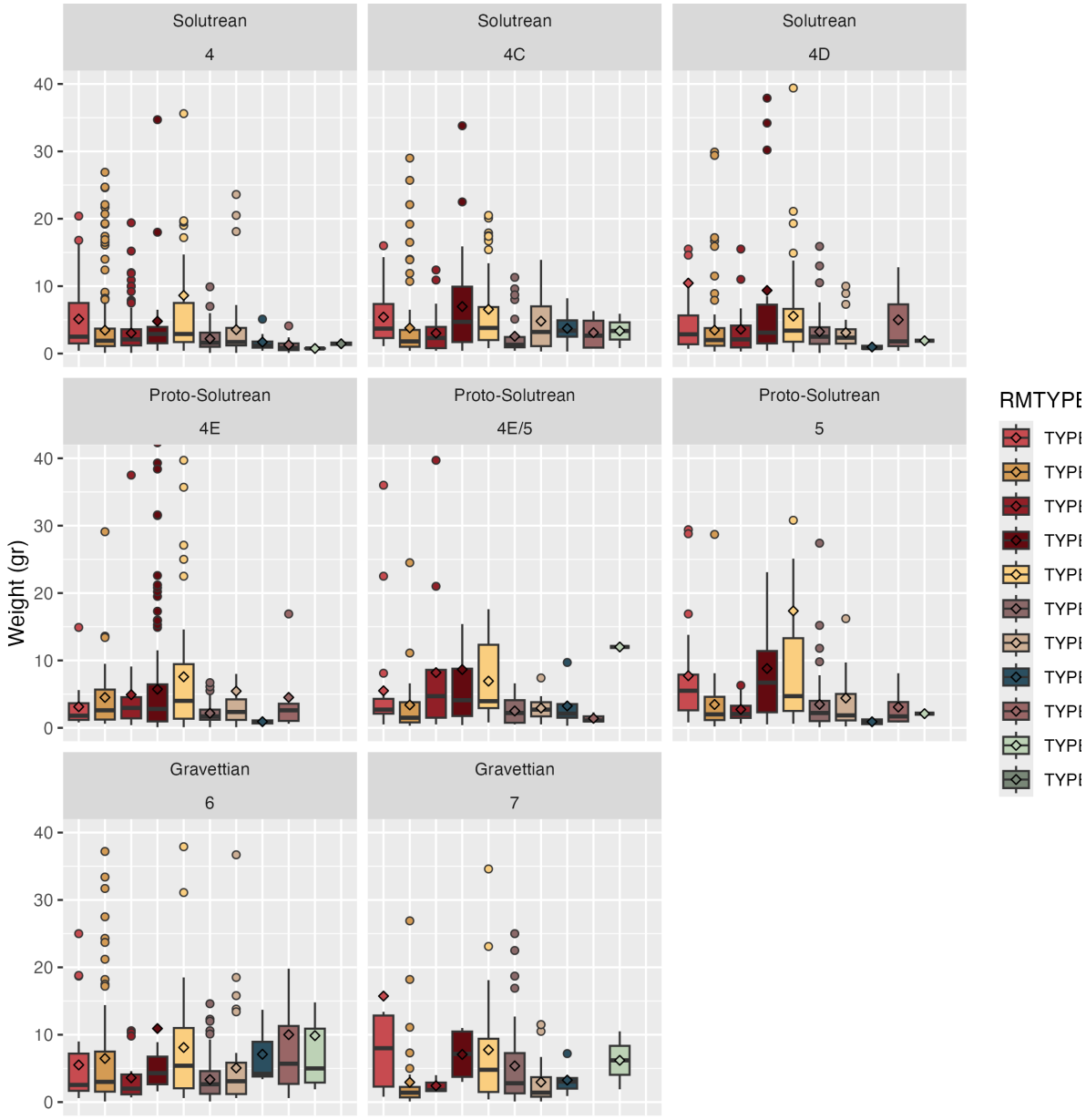

Figure 3.8. Terrace boxplots of chert type weight (gr) per level. Diamond shape within the boxplots represents weight mean. Type 1 to 5 (yellow and red colours) represent local chalcedony and cherts. Type 6, 7 and 9 represent non-local cherts with identified probable provenience (brown colours). Type 8, 10 and 11 represent non-local cherts with non-identified provenience (blue and green colours).

3.3.2.2 Shelter area

The same raw materials found in the Terrace area are also found in the Solutrean occupation of the Shelter, albeit with some differences (Figure 3.9). The local cherts make up between ~65-75% (considering both counts and weight) of the sample and are mainly composed of the brown/yellow cherts (Type 2) that frequently characterise the Lower

Jurassic outcrops of the Algarve (Figure 3.9 a-b). The presence of cherts not congruent with the local sources is, like level 4 in the Terrace, close to 25%, although dominated mostly by Type 6 (~15%). Similarly to the Solutrean occupations of the Terrace, although the artefacts are generally small (lower weights), the local types show a higher variability in mass, with several outliers and heavy samples when compared to the non-local types (Figure 3.9 c).

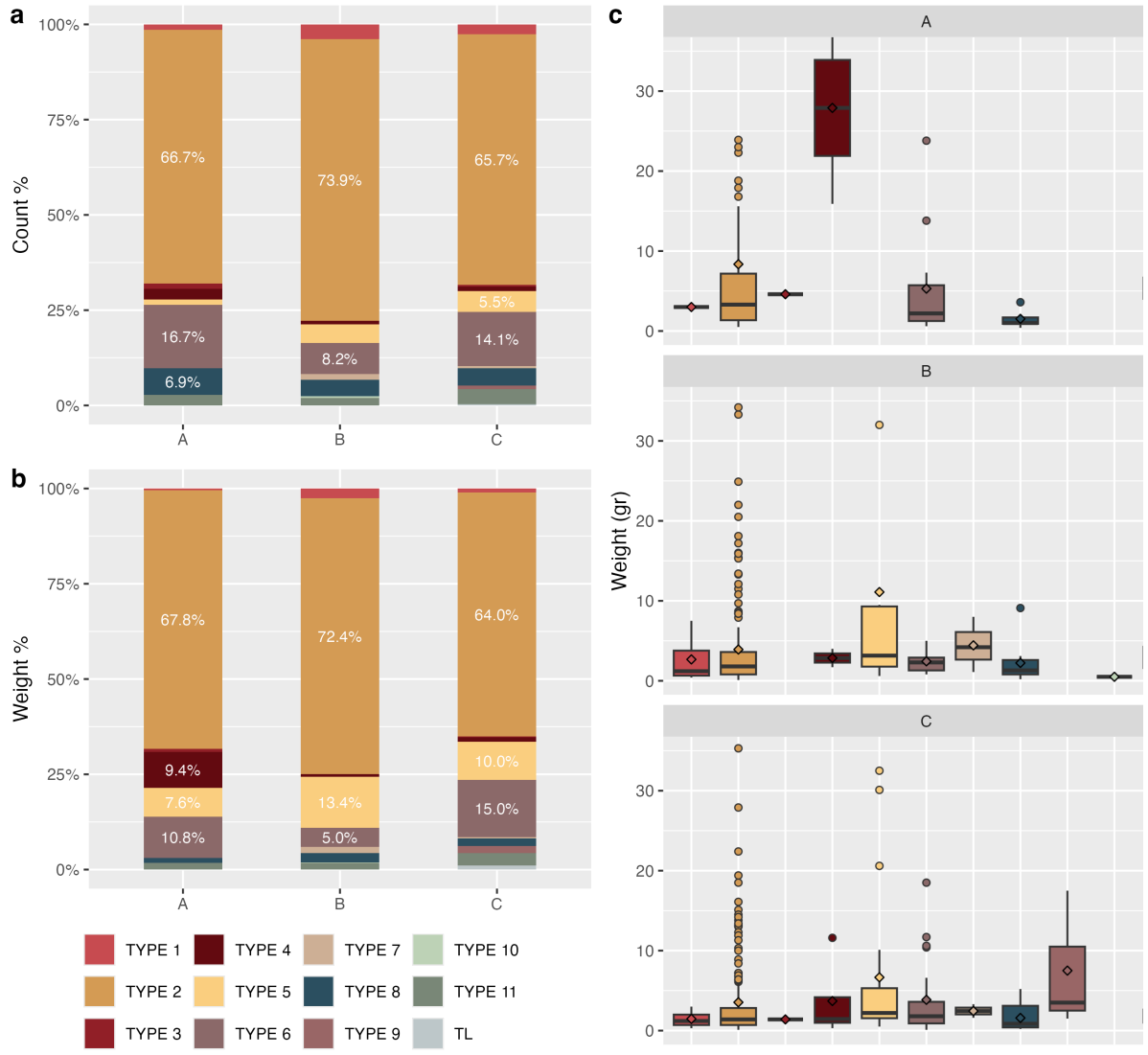

Figure 3.9. a-b) Shelter area chalcedony and chert type frequency (a) and weight sum (b) per level, without unidentifiable samples. Only percentages superior to the 5% threshold are shown in the figure. c) Shelter boxplots of chert type weight (gr) per level. Type 1 to 5 (yellow and red colours) represent local chalcedony and cherts. Type 6, 7 and 9 represent non-local cherts with identified probable provenience (brown colours). Type 8, 10 and 11 represent non-local cherts with non-identified provenience (blue and green colours).

3.4 Discussion

The macroscopic and petrographic analysis of chert and chalcedony lithic materials from the UP levels of the Terrace and Shelter areas at Vale Boi yielded essential insights into the procurement of raw materials and the mobility patterns of hunter-gatherers in southwestern Iberia. These materials serve as valuable indicators for identifying changes in mobility, as they reveal patterns of both local and non-local procurement and have allowed us to answer questions about landscape exploitation and territory movement through the presence (or absence) of local, regional, and long-distance cherts.

The patterns of high percentages of local raw materials in all assemblages indicate a heavy reliance on nearby resources. The local chalcedony and chert indicate that the groups were sourcing a significant portion of their raw materials within approximately a 20 km radius of the site. The direct procurement of these materials is plausible, given that known chalcedony primary sources are situated to the west, about 10 km from Vale Boi (or possibly in the vicinity of the site), and chert sources are found to the east, within the inland Lower Jurassic outcrops, roughly 8 km away (Figure 3.1 b). This hypothesis is supported by the potential existence of UP occupations near these outcrops, which might reflect quarrying and chert catchment activities during prehistory (Zambujo, 1998). Evidence of short-distance procurement at Vale Boi includes the presence of heavy nodules (Figure 3.8) with little indication of knapping and large chunks of chert from local varieties, often with host rock still attached.

It is also possible that local cherts were procured from farther distances, perhaps as part of embedded activities (Pereira et al., 2016a). The chert sources from the Lower and Upper Jurassic periods in western Algarve, located along the beach and cliff areas, can be found between 15-18 km southwest of Vale Boi (Figure 3.1 b). While our current data is not able to pinpoint which specific outcrops were exploited based on macroscopic and petrographic analysis, the identification of persistent coastal adaptions at Vale Boi (Bicho and Esteves, 2022) and exploitation of marine resources such as shells at the site indicates that these groups visited the coast and used the available coastal resources throughout all of the UP (Belmiro et al., 2021; Manne and Bicho, 2011). This suggests that

raw materials could have been conveniently acquired in coastal vicinities without significant detours (Binford, 1979; Surovell, 2009).

The limitations of macroscopic and petrographic methods in discerning between outcrops due to the chert nodule similarities have also impaired the specific distinction between Lower Jurassic and Upper Jurassic sources in western Algarve (within approximately a 20 km radius of the site) and Middle Jurassic cherts located in eastern Algarve (approximately 80 km to the east; Figure 3.1 c). As such, the presence of these regional resources at Vale Boi is uncertain.

A similar issue was noted by Surovell (2009), who described a scenario at the Late Pleistocene archaeological site of Krmpotich (USA), where a specific type of chert found at the site could be sourced from both local and long-distance outcrops. The author suggested that some of these cherts might have been imported from distant sources or previous campsites.

Consequently, we cannot rule out the possibility that some of the cherts we have identified as being sourced within a 20 km radius of Vale Boi may actually be the result of regional procurement and mobility, potentially from areas approximately 80-100 km away, where the Middle Jurassic cherts are located. Given the similarity of the raw materials and the absence of geochemical studies which have shown to be key to differentiating between cherts belonging to the same geological formations or cherts formed under similar conditions (Gómez De Soler et al., 2023), and considering the studies and model mentioned above, most of these cherts likely originate from local sources, while a minor portion may be attributable to regional movements.

In contrast to the Middle Jurassic cherts, the regional Upper Jurassic cherts located ~90 km east of Vale Boi (Figure 3.1 c) have easily discernible characteristics. However, they have not been detected in the assemblages. This absence could be attributed to the limited use and transport of these nodules from their sources to Vale Boi, potentially due to the small size of the nodules (often between 3-5 cm), the difficulty of detaching them from the parent rock, or challenges related to their accessibility and visibility, given that the known outcrops are situated inland, approximately 10 km from the present coastline. This may corroborate the previously observed interest of Pleistocene hunter-gatherers in coastal environments in Iberia (Schmidt et al., 2012), which would have been

characterised by rich marine productivity due to upwelling especially in the Atlantic coast (Bicho and Esteves, 2022; Bicho and Haws, 2008), as well as the aforementioned adaptations and use of coastal resources of hunter-gatherers from Vale Boi (Bicho and Esteves, 2022; Manne and Bicho, 2011).

A similar case is observed for the jaspers located in the SPZ (Oliveira, 1984), located at a minimum of 100 km distance from Vale Boi, as the crow flies. Despite being a source located at closer distances when compared to the cherts of central Portugal or from southwestern Spain, the jasper occurs in trace amounts (n=3) and only in the Gravettian layers (layer 6). Occurring north and northeast, the limited amount of jasper in the assemblage may either represent a limited use of these resources in detriment of the cherts from the Lisbon and Rio Maior area, or suggest that they were used and knapped elsewhere, but not transported, either by the same groups or through exchanges by different groups.

So far, we have discussed the presence of cherts whose outcrops are in relative proximity to Vale Boi and show the full usage of local chert variability (albeit with uncertainty regarding the Upper Jurassic cherts of western Algarve due to their macroscopic similarities) and the selective usage of regional cherts within the Algarve. As previously mentioned, however, it is the combined identification of local and long-distance cherts that allows us to have a better idea of the total exploited territory, as well as the possible existence of exchanges and social networks between groups occupying different territories.

Although a wide variety of chert types incongruent with the regional reference collection were identified throughout the stratigraphy and classified as non-local, we were only able to ascertain the possible sources of three types: Type 6, Type 7 and Type 9. The long-distance cherts with identified sources come from distances of over ~200 km and in two main directions: 1) from the north, where Cretaceous cherts from central Portugal are found (Figure 3.1 a); and 2) from the east, where peloidal/oolitic chert from western Andalusia is present (Figure 3.1), and possibly jasper, transported by the Guadiana river at the current border between Portugal and Spain.

In fact, Vale Boi's proximity to a coastal setting, with access to beaches, as well as rivers such as the Guadiana River, where raw material nodules could be transported from

far-away distances, could explain the presence of long-distance cherts. In this case, the presence of cherts with sources from over 200 km would be explained by their procurement in secondary settings and a possible local movement range. However, the scarcity of pebble cortex and the predominance of rounded cortex suggest that these cherts were likely not collected from beaches or riverbeds far from the outcrops but were possibly gathered closer to the source areas (Kuhn, 2004). As such, the presence of these long-distance cherts is better explained by the extended movement of human groups in the south-north and west-east axes.

However, it is relevant to ask why human groups occupying Vale Boi were obtaining a considerable amount of their chert from such long distances and such specific directions, either directly through procurement or through exchanges with other groups. Although the source of the other non-local cherts is still unknown, making the directions and distances to obtain them also unknown, the identified axes of long-distance movement to the north and east may be the result of the influence of the topography on mobility patterns. Indeed, formal models that seek to explain hunter-gatherer mobility have highlighted the significance of factors such as topography on the distances travelled by groups or individuals (Brantingham, 2006).

Similarly, friction of terrain cartography for Iberia has shown that terrain can produce different costs of travelling on foot, which differ from those directly observed on current-day maps and direct distances (Díaz del Río, 2020). In this context, distance is less related to measurements and more related to the time it costs to go from point A to point B (Zilhão, 2021). For example, Díaz del Río (2020) highlights the existence of low-cost pathways through plateaus and the connectivity between the river valleys of central and south Iberia (Guadalquivir, Guadiana and Tagus).

Using the same friction of terrain cartography, Zilhão (2021) also identifies the possible role of terrain in hunter-gatherer mobility in the Upper Palaeolithic. For example, the author highlights that the Parpalló bifacial point is found across central/south Spain and Portugal during the Upper Solutrean, and thus is considered the index fossil for this period in the region. From westernmost central Portugal to easternmost central Spain (west-east axis across Iberia), there is a distance of ~800-900 km as the crow flies. However, the Parpalló point is not found in northern Spain (Catalunya), only 200 km north of the easternmost site where the index fossil was

identified. The author suggests that this separation may be explained by the friction of terrain, which divides Iberia into two halves, creating a quicker mobility pathway between central/south Spain and Portugal in opposition to the higher-cost time necessary to travel to northern Spain.

As such, the observed long-distance transfer of cherts in the north/east directions by hunter-gatherers at Vale Boi might reflect this central and southern Iberia territory dynamic and the exploitation of the natural corridors for movement, explaining the substantial use of long-distance chert. In this case, the presence of a smaller subset of non-local cherts of unknown origin (TL) but not knapped at the site could represent different forms of long-distance trade of finished goods and blanks, or interactions with various social networks, potentially even indicating individual networks and mobility strategies (sensu Gamble, 1999).

Another key idea about these mobility patterns is not only their distance and direction but also their continuity throughout the UP. The detection of the same types of non-local raw materials throughout the stratigraphy at Vale Boi points to a persistent use of long-distance chert sources. This continuity cannot only be explained by the natural topographic connectivity between central and south Iberia but can also be attributed to a tradition of shared knowledge and culture regarding the locations of raw materials and other resources within the landscape, or the preservation of social networks over time.

For example, Cascalheira et al. (2017b) acknowledge the adoption of specific behavioural strategies by Vale Boi hunter-gatherers in response to the regional ecological conditions, which were sustained throughout the UP at the site. Practices such as grease rendering or the functional specialisation of raw materials (e.g., the use of quartz and greywacke for bone breakage activities or quartz for grease rendering) are seen as deliberate actions with significant cultural implications for future generations, influencing the adaptive choices made over time. Accordingly, chert raw material acquisition and management appear to be integral to these behavioural strategies, established from the site's earliest occupations and perpetuated throughout the UP.

However, despite the consistent presence of local and long-distance chert throughout the stratigraphy, we identified trends of changing frequencies in the different occupations, possibly also providing different interpretations about mobility and social

behaviour through time. For example, the significant presence of non-local cherts during the Gravettian occupations at Vale Boi suggests extensive communication and mobility among the groups occupying the site. As previously established, however, while it would be expected for Solutrean groups to have high mobility and extended social networks, the opposite would be expected for the Gravettian occupations. As such, our results, especially those from the Gravettian occupations, diverge from the anticipated patterns.

Specifically, technological analyses of lithic assemblages have unveiled notable differences between Gravettian assemblages from the Atlantic and Mediterranean coastal regions, pointing to the existence of two distinct regional Gravettian traditions in southern Iberia: the Vicentine Gravettian at Vale Boi, and the Mediterranean Gravettian identified in UP sites in southern Spain (Marreiros et al., 2015; Marreiros and Bicho, 2013). These traditions are thought to reflect adaptations to the unique local and regional ecological settings (Bradtmöller et al., 2016) and evolving environmental conditions (Marreiros and Bicho, 2013), potentially fostering distinct ethnographic divisions among hunter-gatherer communities (Marreiros et al., 2015). Consequently, it would be expected for territorial or cultural demarcations to influence material usage patterns, with a shift towards a greater reliance on local resources and a diminished use of non-local raw materials during the Gravettian at Vale Boi.

However, the observed prevalence of non-local chert materials could reflect not merely long-distance movements within a single cultural framework but rather the result of interactions and exchanges between different cultural groups, thus explaining the existence of distinct regional technological characteristics.

This perspective aligns with Brantingham's (2006) discussion on social exchange, which posits that exchanges likely occurred between groups occupying distinct territories, who would meet regularly to trade raw materials. This model helps explain the presence of materials from distant sources at archaeological sites, illustrating the nuanced and interconnected nature of prehistoric social landscapes (Whallon, 2006).

In this sense, interpreting the ubiquitous presence of long-distance chert at Vale Boi as a result of exchange between groups and social networks informs us that even during chronological periods where ethnographic boundaries have been suggested, there is communication and exchange between groups. This further cements the idea of

interconnectedness across the Iberian territory during the UP, expanding the extensive line of contacts and networks identified across north and central Iberia (Aubry et al., 2016, 2004; Corchón Rodríguez et al., 2016; Lombera-Hermida et al., 2016; Marreiros et al., 2016; Ortega, 2003; Sánchez de la Torre et al., 2023) to southwesternmost Iberia.

However, although social networks may explain the presence of long-distance cherts at Vale Boi even during periods of demarked regional boundaries, the high/low presence of long-distance raw materials at the site may not be the direct result of a higher reliance on these networks, or their expansion or shrinkage.

An alternative interpretation of the varying frequencies of non-local cherts during different periods at Vale Boi can be explained by the "Mean per Capita Occupation Span" model proposed by Surovell (2009), and the "Distance/Frequency Index (DFI)" outlined by Grove et al. (2023). These models hypothesise that shorter-term occupations are likely to show a higher proportion of non-local artefacts, whereas with longer-term settlements, the prevalence of local artefacts increases. This pattern may be attributed to environmental influences: challenging conditions such as fragmented habitats and cooler temperatures limit mobility, making long-term settlement in areas rich in local resources a preferable, lower-risk option (Surovell, 2009).

This pattern is mirrored in the archaeological record of Vale Boi, where, aside from the earlier Gravettian of levels 6 and 7, subsequent occupations seem to adopt a logistical-settlement strategy, positioning Vale Boi as a long-term basecamp (Cascalheira et al., 2017b). In this context, the Gravettian phase at Vale Boi could reflect a period of enhanced mobility and brief occupations, possibly interspersed with reoccupations, indicative of a significant import of non-local raw materials. This scenario parallels observations from the Late Gravettian in the French Massif central, where hunter-gatherer groups are known to have transported entire or pre-formed blocks of raw material over considerable distances (> 200 km) for short-term, hunting-related site occupations (Delvigne et al., 2019). The authors also note that in the following occupations, during the Badegoulian and Magdalenian, occupation duration increases along with a significant increase of local and semi-local raw materials.

Similarly, the lower percentages of non-local cherts characterizing the phases following the Gravettian at Vale Boi could reflect a period of increased site occupation. In

this context, and following the model by Surovell (2009), the shift toward colder and drier climatic conditions marked by Heinrich Event 2 (HE2) during the Proto-Solutrean, followed by the Last Glacial Maximum in the Solutrean period (Belmiro et al., 2021; Cascalheira and Bicho, 2013; González-Sampériz et al., 2010; Sanchez Goñi and Harrison, 2010; Schmidt et al., 2012), could have resulted in a more challenging environment with sparser vegetation (Cascalheira and Bicho, 2013; González-Sampériz et al., 2010). These changes likely constrained the mobility of hunter-gatherers, fostering longer-term settlements within the resource-rich niche of southwestern Portugal (Cascalheira et al., 2017b; Schmidt et al., 2012). Consequently, as settlements extended in duration, the reliance on non-local raw materials, whether sourced directly or acquired through trade, diminished in favour of increasingly dominant local raw materials.

3.5 Conclusions

Our findings build upon earlier studies indicating that the majority of chert utilized at Vale Boi originates from local Lower Jurassic sources within a 20 km radius of the site (Pereira et al., 2016a), with non-local materials constituting a relevant portion of the chert used. The hypothesis of long-distance procurement of Cretaceous cherts from central Portugal, situated north of Vale Boi, is corroborated by visual and petrographic evidence (Bicho et al., 2013; Pereira et al., 2016a), and this pattern persists throughout the UP. Furthermore, the identification of cherts bearing macroscopic resemblance to the peloidal/oolitic Upper Jurassic cherts from the Betic System in southern Spain confirms a west-east mobility axis, previously inferred from techno-typological studies, also spanning the entirety of the UP period.

These findings reveal a landscape of hunter-gatherers engaged in complex practices of resource management, and possibly risk management. The presence of allochthonous raw materials, albeit in small quantities during the Proto-Solutrean and Solutrean phases, underscores that the inhabitants of Vale Boi—situated on the periphery of Iberia and Europe, bordered by the sea to the south and west, and confined to the patchy refugia created by the worsening climatic conditions of the HE2 and following Glacial Maximum (Schmidt et al., 2012)—were certainly not isolated. Instead, they were part of an extensive social network, a pattern of interconnectivity that

resonates with findings across western Europe (Aubry et al., 2016, 2004; Corchón Rodríguez et al., 2016; Lombera-Hermida et al., 2016; Ortega, 2003; Sánchez de la Torre et al., 2023).

In southern Portugal, this interconnection among UP hunter-gatherers from diverse and distant regions of Iberia is similarly observed. This was already expected for the Proto-Solutrean and Solutrean occupations, but less so for the Gravettian where social boundaries were expected based on previously identified technological facies between regions (Marreiros et al., 2015). Instead, our results show a high presence of long-distance raw materials during the Gravettian occupations, which may indicate that social networks were established from the first UP occupations in south Portugal and maintained through time.

The outcomes of this research pave the way for continued exploration of these assemblages through diverse methodologies. Future directions include employing a geochemical approach to both the studied assemblages and the geological reference collection, aiming to enrich discussions on mobility throughout the UP at Vale Boi. This approach is anticipated to provide diagnostic elements to distinguish between cherts from Lower and Middle Jurassic units, thereby offering a comprehensive view of regional resource utilisation and mobility patterns.

Additionally, experimental replication and the creation of a reference collection modified through heat treatment could enhance the identification of raw material types and currently indistinguishable samples, as noted in prior research (Pereira et al., 2016a). Lastly, we intend to integrate technological data from current and ongoing datasets to delve deeper into the usage and management of raw materials (both local and non-local) over time, their association with different site uses, and to contextualize these practices within the broader framework of human adaptations to changing environmental conditions throughout the UP.

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4. Within chert: a multi-technique mineral and geochemical approach to the study of chert of southwestern Iberia

In preparation for publishing

Abstract

Recent advances in the study of chert in the Algarve have applied macroscopic and petrographic methods to geological samples from regional chert-bearing formations and archaeological materials from the Upper Palaeolithic assemblages of Vale Boi to explore hunter-gatherer mobility and technological organisation. However, some questions regarding human behaviour, mobility, and raw material selection remain unanswered. This study expands the characterisation of both geological and archaeological samples through the application of additional analytical methods, aiming to address critical research questions and assess the potential of these methods for chert characterisation in the Algarve and at Vale Boi. The results demonstrate that a multi-layered analytical approach is most effective for chert characterisation. While the applied geochemical methods yield strong results in distinguishing between cherts of different geological periods, they struggle to differentiate between cherts from the same period but different epochs. Building on previous analyses, this research contributes to broader discussions on lithic procurement strategies, human mobility, and exchange networks in southwestern Iberia during the Upper Palaeolithic.

Keywords: Geoarchaeology; XRD; SEM-EDS; pXRF

4.1 Introduction

The study of lithic raw materials has been a key topic in archaeology, as stone tools are ubiquitous in the archaeological record and identified as key element in hunter-

gatherer cultural, economical and social organisation (Andrefsky, 1998, 1994; Gamble, 1999; Odell, 2006; Shott, 1986; Tostevin, 2012). Among these materials, chert played a crucial role in lithic tool production, making its study, characterisation and sourcing a key issue in archaeological research, particularly in Upper Palaeolithic (UP) assemblages (Brandl, 2016, 2013; Eixea et al., 2023; Jensen, 1988; e.g., Larick, 2011; Luedtke, 1979; Soto et al., 2018; Tomasso et al., 2019). Determining the origins of chert artefacts reveals patterns of raw material availability and provides valuable insights into prehistoric procurement strategies, territorial behaviours, and long-distance exchange networks over time (Ambrose and Lorenz, 1990; Binford, 1980; Kuhn, 1994; Surovell, 2009; Torrence, 1986; Whallon, 2006).

Chert sourcing studies have frequently relied on macroscopic and petrographic techniques, providing valuable insights into raw material formations and procurement by hunter-gatherer groups (e.g., García-Simón and Domingo, 2016; Gómez de Soler et al., 2020; Matias, 2016; Tomasso et al., 2019). While these methods remain essential in lithic sourcing, they can also have limitations. Their reliance on physical appearance and petrographic homogeneity can make it difficult to distinguish geologically similar cherts, especially in cases of long-distance procurement. Moreover, although macroscopic analysis is non-destructive, thin section petrography requires destructive sampling, raising concerns about the preservation of archaeological materials (Brandl, 2016; Luedtke, 1992).

Recent research has increasingly incorporated geochemical and spectroscopic techniques to address these challenges and refine chert sourcing methodologies. Luedtke (1978, 1979, 1992) highlights the value of chemical data combined with multivariate statistical analysis, while Brandl (2016) integrates petrographic and geochemical approaches within the Multi-Layered Chert Sourcing (MLA) framework.

As seen in the previous chapters, we have applied macroscopic and petrographic approaches to the study and characterisation of cherts from the Algarve region (Belmiro et al., 2025, 2023). However, the chert-bearing formations from the Algarve region remain largely unexplored through other analytical techniques.

An exception would be the Lower Jurassic (Carixian) and Upper Jurassic (Kimmeridgian) limestone and dolomitic limestone formations from western Algarve

(Rocha et al., 1979), which show previous mineral and geochemical characterisations (Ribeiro, 2005). However, given the geological scope of the study, only 3 chert samples from the Carixian and 3 samples of the Kimmeridgian were analysed. While providing a basis for mineral and chemical composition of these cherts, it is key to expand the analysis to a more robust sample size.

Similarly, the UP chert assemblages from the site of Vale Boi have yet to be further characterised through geochemical methods. These may be key to address open research topics and questions by recent studies focusing on chert provisioning and selection during the UP at Vale Boi.

For example, the Lower Jurassic (Carixian) cherts, located near Vale Boi (<20 km) show macroscopic and petrographic similarities to the Middle Jurassic (Malhão formation) cherts located eastwards (>70 km). This makes the differentiation between specific chert formations unclear (Belmiro et al., 2023). Making this distinction is critical for understanding regional mobility patterns and whether local cherts at Vale Boi are a mix of local (<30 km) and regional (30-120 km) resources (Herrero-Alonso et al., 2020; Tarriño et al., 2015).

Questions regarding nodule selection may also be further explored to characterise close-range chert procurement. This is particularly relevant for the Lower Jurassic (Carixian) cherts, which show different degrees of dolomitization, with a clear impact on the knapping quality. By further characterising the mineral and chemical composition of geological cherts from all outcrops and macroscopic variability, and comparing with the archaeological samples, we may explore behaviours related to selection associated with nodule quality (sensu higher silicification).

Additionally, evidence suggests that non-local materials and products were frequently introduced into the archaeological site, indicating complex long-distance procurement dynamics. However, these findings were based on macroscopic and petrographic studies, which leaves room for further characterisation to strengthen source attributions and test current hypotheses. This is especially relevant for archaeological chert types for which we did not have a direct comparison regarding petrography, as for example T7 possibly originating from the Betic systems (south Spain) or other types for which a source could not be identified (T9-11).

To further explore these questions and topics, this study employs an integrated analytical approach to geological chert samples from local, regional, and non-local (allochthonous) formations, as well as archaeological assemblages from the UP levels of Vale Boi to accomplish the following goals:

- Expand the characterisation of chert samples from the Algarve region, including data on their mineral and chemical composition. This will deepen our understanding of the characteristics of siliceous raw materials across the region and make this information accessible to the scientific community through its integration in our online lithotheque (https://lusolit.icarehb.com).

- Assess the potential of mineral and chemical analyses to distinguish between macroscopic and petrographically similar chert samples from the Lower Jurassic Carixian (west Algarve) and Middle Jurassic Malhão (east Algarve) formations.

- Use geochemical methods to further characterise the archaeological samples, as well as geological samples from other regions of interest (e.g., Cretaceous cherts from central Portugal and cherts from the Betic Systems of southern Spain). This will enable us to compare the geological and archaeological data, testing, corroborating, and strengthening the petrographic and macroscopic source attributions of archaeological chert types. Additionally, comparing local geological and archaeological data may provide valuable insights into the selection of nodules for knapping, especially considering the known process of dolomitization in the Lower Jurassic outcrops.

- Test the potential of various techniques and approaches to enhance the interpretation of archaeological chert raw materials and human mobility patterns. Specifically, we will assess whether these methods effectively characterise and differentiate between chert types from various formations, both regional and long-distance, and enable accurate source attribution of archaeological lithic artefacts.

To accomplish these goals, we apply three different methods: X-Ray Diffraction (XRD) to regional Algarve chert samples; Scanning Electron Microscopy coupled with X-Ray Microscopy (SEM-EDS) to regional Algarve chert samples and all identified chert types from the UP sequence at the Terrace of Vale Boi; and portable X-Ray Fluorescence

(pXRF) to all previously mentioned samples, including additional chert samples from central Portugal (Rio Maior region) and southern Portugal (Betic systems).

By refining the characterisation of chert in the region, improving source attribution from archaeological lithic assemblages, and identifying the strengths and weaknesses of different analytical methods, this research contributes to broader discussions on lithic procurement, human mobility, dissemination of products and exchange networks in southwestern Iberia during the UP.

4.2 Materials and methods

Given the particularities of each analytical technique used in this study, availability of samples and level of destructiveness on the artefacts, and research questions, different samples were used in each method. These methods, their application in chert characterisation studies, especially in Iberia, and summarised methodology are further discussed below.

Table 4.1 shows the samples used for each method. These included chert geological samples from different regions of Iberia, with a focus on the Algarve region. The Algarve materials include geological samples from the western and eastern Algarve basin collected from 2021 and 2022 prospection works (Figure 2.3) (Belmiro et al., 2023). The western groups include the Triassic formation cherts (fibrous chalcedony), also identified as chalcedony (Triassic west, hereon TW), the Lower Jurassic (Carixian) formation (Lower Jurassic west, hereon LJW; Figure 2.4 and Figure 2.5) and Upper Jurassic (Kimmeridgian) formations (Upper Jurassic west, hereon UJW; Figure 2.6) (Ribeiro, 2005; Rocha et al., 1979; Terrinha et al., 2006).

Table 4.1. Number of samples used for the XRD, SEM-EDS and pXRF study by a) geological formation for the geological samples, and by b) type for the archaeological samples.

a) Geological	XRD	SEM-EDS	pXRF
LJW	12	14	40
TW	1	1	2
UJW	1	4	4
MJE	5	10	14

UJE	4	10	6
CPT	-	-	16
UCA	-	-	12
Total (a)	**23**	**39**	**94**
b) Archaeological	**XRD**	**SEM-EDS**	**pXRF**
T1	-	3	5
T2-5	-	11	31
T6	-	4	13
T7	-	5	7
T8	-	1	8
T9	-	1	3
T10	-	2	3
T11	-	-	2
Total (b)	**-**	**27**	**72**
Total (a+b)	**23**	**66**	**166**

The eastern groups include the Middle Jurassic (Malhão) formation (Middle Jurassic east, MJE hereon; Figure 2.7) and the Jordana formation (Upper Jurassic east, hereon UJW; Figure 2.8) (Manuppella et al., 2007; Terrinha et al., 2006).

Other geological samples included in the study were the central Portugal (Rio Maior region) cherts from the Cretaceous formation (hereon CPT) (Matias, 2016), previously prospected and collected by previous researchers (Pereira et al., 2016b), and cherts from the Upper Jurassic of the Betic systems (hereon UCA) (Rodríguez et al., 2011), obtained from the lithotheque of the Unit of Geoarchaeology and Archaeometry Applied to Historic Artistic and Monumental Heritage (University of Cadiz).

The archaeological samples used for the study are from the archaeological site of Vale Boi, mainly the Terrace and Shelter areas. The samples were chosen based on the groups identified in our previous works (Belmiro et al., 2025), with T1-5 archaeological cherts corresponding to local types, T6 possibly originating from central Portugal Cretaceous formation, T7 and T9 with sources possibly from southern Portugal Betic systems and T8 and T10-11 without a current identified source (Table 3.3).

For further reproducibility and replicability and working towards the goal of open science (Marwick, 2017), all analyses were performed through R Studio. The R code used for the analysis, datasets, and visual representations presented in this paper is available through our online repository (https://doi.org/10.17605/OSF.IO/DBFT2). We utilised the rrtools package by Marwick et al. (2018) to create a research compendium and

produce a reproducible journal article. The repository includes the complete set of raw data used in the analysis, along with a custom R project (Wickham, 2015) that contains the necessary code to generate all tables and figures. To facilitate broad reuse, the code is provided under the MIT license, the data under CC-0, and the figures under CC-BY.

4.2.1 X-Ray Diffraction

X-ray diffraction (XRD) is a widely used laboratory technique for examining the atomic structure of crystalline materials (Adams, 2005). Most of the minerals in siliceous rocks are crystalline in nature, meaning their atoms are arranged in a three-dimensional repeating pattern. The crystal structure is defined by the arrangement of atoms within a single unit cell, as well as the cell's size and shape.

XRD works by directing a beam of X-rays onto a crystal, causing the rays to diffract and produce a characteristic diffraction pattern. The d-spacings—the distances between parallel planes of atoms in the crystal lattice—are derived from the angular positions and intensities of the diffracted beams. These d-spacings serve as a unique fingerprint for crystalline compounds, allowing for mineral identification (Marshall and Fairbridge, 1998).

Although powder-XRD is a destructive technique, it has been used alongside petrographic characterisation (thin section analysis) to gain a comprehensive understanding of the petrographic and mineral composition of lithic raw materials, such as chert, in both geological and archaeological contexts. This combined approach enables comparisons with potential archaeological implications, particularly in raw material sourcing studies in the Iberian Peninsula (e.g., Columbu et al., 2023; Gómez De Soler et al., 2023; Ortega et al., 2018).

This study utilised X-ray diffraction (XRD) to determine the mineral composition of 23 geological powdered samples of chert from the Algarve region (Table 4.1). These samples represent at least one specimen from each outcrop, with a focus on primary and sub-primary locations across all chert-bearing formations in the region. A detailed description of the sample preparation process is available in our online research repository (Online resource 1).

The samples were analysed using a Bruker AXS D8 Discover XRD with the Da Vinci design, equipped with a Cu Kα source operating at 40 kV and 40 mA, and a Lynxeye 1D detector. Scans were conducted from 3° to 75° 2θ, with a 0.05° 2θ step, at the HERCULES Laboratory, University of Évora.

Preliminary phase identification was performed using Diffrac.Suite™ (Bruker) and further refined with Profex (version 5.2.9) after converting raw files using PowDll Converter. All data processed in Profex was organised and plotted in R Studio, where visual representations of the XRD data were also generated.

Three additional samples (SP21, SP40, and a geological sample from the Triassic outcrop of Western Algarve) had previously been sent for XRD analysis and interpretation at Geociencias Barcelona-CSIC (Table 4.1). The analysis was conducted using a Bruker D8-A25 XRD, equipped with a Cu source (wavelength λ = 1.5405 Å) and an ultra-fast PSD detector (Lynxeye). The diffraction spectrum data were interpreted using the Diffrac.Suite software by Bruker by a technician.

4.2.2 Scanning Electron Microscopy-X-Ray Microscopy

Scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDS or SEM-EDX) provides various types of data by combining SEM imaging with elemental analysis. SEM is an electron microscopy technique that generates high-resolution images by directing a beam of electrons onto a specimen's surface. As the electron beam interacts with the sample, it scatters as backscattered electrons and emits X-rays. As different atomic elements release characteristic X-ray at specific energies, it is possible to identify the elements present in the sample (Kirkbride, 2000) using an energy dispersive detector (EDS).

Although SEM-EDS is a versatile and efficient method, EDS has a relatively high chemical analysis limit of detection (Kirkbride, 2000).

Despite this limitation, EDS coupled with SEM has been widely used alongside other techniques, such as petrography, XRD, and XRF, to characterise geological and archaeological lithic resources, including chert raw materials. This combined approach enhances the understanding of a formation's characteristics and has aided in identifying

sources in provenance studies in the Iberian Peninsula (e.g., Abrunhosa et al., 2020; Columbu et al., 2023; Costa et al., 2022; Ortega et al., 2018).

This study employed scanning electron microscopy and energy-dispersive X-ray spectroscopy (SEM-EDS) to analyse the surface structure and elemental composition of the samples. The analysis included 39 geological samples from all five chert-bearing formations (Table 4.1). Additionally, 27 samples were examined from archaeological artefacts, representing all previously identified chert types (Table 4.1).

The samples consisted of lithic chips mounted in resin and sanded until minimal to no scratches were visible under the microscope. A detailed description of the sample preparation process and analysis is available in our repository (Online resource 1).

The chip analysis was conducted at the HERCULES Laboratory (Évora) using a variable pressure Hitachi S3700N SEM, coupled with a Quantax EDS microanalysis system. Specifically, the Quantax system is equipped with a Bruker AXS 5010 XFlash Silicon Drift Detector, which offers a spectral resolution of 129 eV at FWHM for MnKα. The EDS elemental analysis and quantification was carried out with the ESPRIT software by Bruker.

The analysis focused on identifying representative traits of the samples for characterisation and comparison. Images were captured at 250x and 1000x magnification for each analysed sample. To determine the elemental composition, elemental maps and spectra were generated, providing both visual and semi-quantitative data on the selected elements and sample regions. At least one map or spectrum was obtained for each distinct type of inclusion or structure identified in the samples.

4.2.3 Portable X-Ray Fluorescence

X-ray Fluorescence (XRF) works by irradiating the specimen with X-rays, which causes electrons to attain an excited state. The specimen emits X-rays (fluorescence) when the atom returns to ground state; this energy is characteristic of the atoms present in the sample. As such, XRF spectra contain information about the chemical elements present in the analysed sample (Kirkbride, 2000).

However, laboratory-based XRF has the limitation of being non-portable and requiring sample preparation, which is often incompatible with archaeological studies where assemblages cannot be transported or destroyed. In this context, portable XRF (pXRF) instruments offer a practical alternative. These devices are easily transportable, non-destructive, and have been successfully used in source discrimination studies, where they provide comparable results to their laboratory-based counterparts, although with a lower detection limit (Craig et al., 2007).

pXRF has been used to discriminate between sources of various lithic raw materials, mainly with obsidian (e.g., Craig et al., 2007; Gemici et al., 2022; Nazaroff et al., 2010; Tykot, 2002), as well as other materials like volcanic and metamorphic rocks (Egeland et al., 2019; Grave et al., 2012).

Studies on chert archaeological assemblages in the Iberian Peninsula have also employed pXRF to distinguish between sources. When combined with other methods, pXRF has provided valuable insights (Costa et al., 2022; Gómez De Soler et al., 2023; Pereira et al., 2021; Pereira et al., 2016a).

For this study, a Bruker portable XRF Titan S1 was used in a laboratory benchtop setup, powered by battery (with up to 25% battery charge before being replaced by a fully charged battery). The standard databases available in the equipment from Bruker were employed: Geochem application and the Dual Mining method. A detailed description of the preparation and analysis process and a description of the elements and compounds used in the statistical analysis are available in our online repository (Online resource 1 and 3, respectively).

Chert samples from various sources and types, including both geological (94) and archaeological (72) specimens, were scanned (Table 4.1). After scanning, the thickness and diameter of the scanned face were measured to ensure that each sample met the minimum required thickness and size (Newlander et al., 2015) (Online resource 2).

For geological samples, fresh, flat surfaces were scanned, avoiding altered faces or cortex. When necessary, the samples were prepared by breaking the nodules. The samples selected represented all varieties of chert identified in the Algarve region, as well as in the archaeological record of Vale Boi. Additional samples were included from other regions, such as central Portugal and southern Spain, to facilitate comparisons and test

hypotheses based on macroscopic and petrographic data. For archaeological samples, artefacts were chosen from previously identified types, prioritising larger, flatter morphologies with minimal surface alterations.

The analysis and reporting protocol were established based on previous studies, emphasising both the accuracy of the obtained data and the transparency and reproducibility of the results (Johnson et al., 2024; Newlander et al., 2015). The analysis focused on descriptive statistics and the generation of ANOVAs to compare different groups.

4.3 Results

The results presented in this section focus on the main observed patterns of the analysis between outcrops, formations and chert types. The detailed analysis/graphs regarding individual samples for all methods can be found in our online repository (Online resource 4).

The XRD results are homogeneous, showing little differences between samples (Table 4.2). The samples are predominantly composed of quartz (Figure 4.1 and Figure 4.2). Dolomite and calcite were also identified in several samples (>7), and in the samples processed by the Geociencias Barcelona-CSIC, moganite and gypsum were identified. Despite this homogeneity, the results show some patterns in the presence of dolomite and calcite.

Dolomite was mainly identified in the samples from LJW and TW outcrops (Figure 4.1). Small dolomite peaks are present in more than ~60% of the LJW cherts and the single sample from the TW. In comparison, only 1 of the 11 samples from the Middle and Upper Jurassic outcrops showed the presence of dolomite.

In opposition, calcite was mainly identified in the Upper Jurassic samples and the TW samples. The primary and sub-primary cherts from the UJE and the UJW all show the presence of calcite peaks (Figure 4.2). In comparison, only 1 sample out of 12 of the LJW and 1 out of 5 of the MJE show the presence of calcite.

Table 4.2. Identified crystalline phases of chert geological samples from the Algarve.

Sample	Outcrop	Quartz	Dolomite	Calcite	Moganite	Gypsum	Halite
SP6_CSV	LJW	xx	xx				
SP7_CSV	LJW	xxx	(x)				
SP10_PdA	LJW	xxx		(x)			
SP14_PBX	LJW	xxx	(x)				(x)
SP15_PBX	LJW	xxx	(x)				
SP18_PBX	LJW	xxx	(x)				(x)
SP21_BLS	LJW	xxx			x*		
SP28_ASP	LJW	xxx	(x)				
SP30_FZF	LJW	xxx	(x)				
SP33_FZF	LJW	xxx	(x)				
SP34_PdA_a	LJW	xxx					
SP40_FER	LJW	x		x /x*			
TABUAL	TW	x*	x*	x*	x*	x*	
SP69_MAR	UJW	xxx		(x)			
SP50_CdC	MJE	xxx					
SP52_GUI	MJE	xxx	(x)	(x)			
SP62_OLV	MJE	xxx					
SP63_OLV	MJE	xxx					
SP66_MALH	MJE	xxx					
SP57_JOR	UJE	xx		xx			
SP58_JOR	UJE	xx		xx			
SP59_JOR	UJE	xx		xx			
SP61_PER	UJE	xxx		(x)			

Legend: LJW: Lower Jurassic west (Carixian formation); UJE: Upper Jurassic west (Kimmeridgian formation); TW: Triassic west; MJE: Middle Jurassic east (Malhão formation); UJE: Upper Jurassic east (Jordana formation). (*) refers to results obtained from samples analysed and interpreted at the Geociencias Barcelona-CSIC. Content percentages of samples analysed at the Hércules laboratory are represented by x: xxx refers to > 90%; xx to 90-30%; x to 10-1%; (x) to <1%.

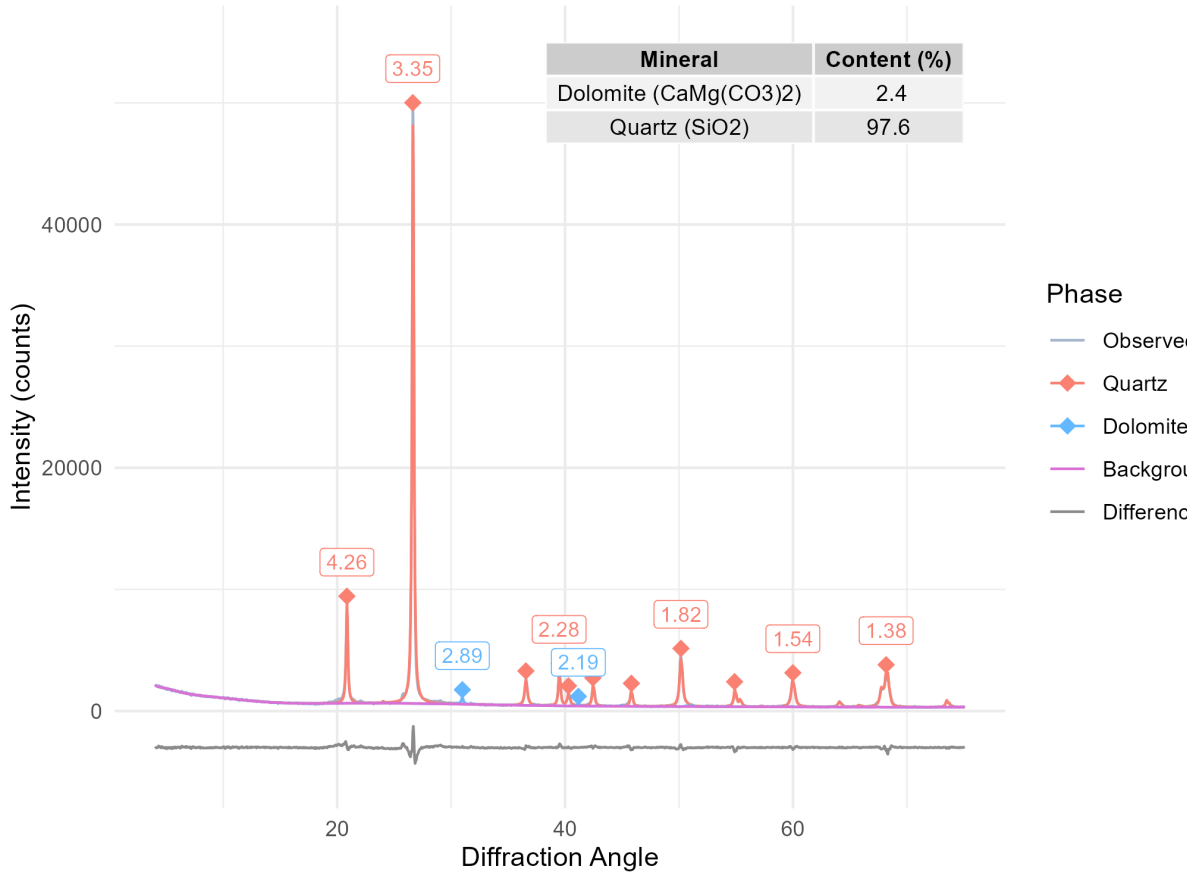

Figure 4.1. Plot of minerals identified through XRD in the LJW chert sample from the outcrop Praia do Belixe (SP15_PBX). The rhombus shape signifies the main peaks key to identify each mineral. Labels represent the d spacing values of key mineral peaks. Quantifications presented in the supporting table were obtained using Rietveld refinement.

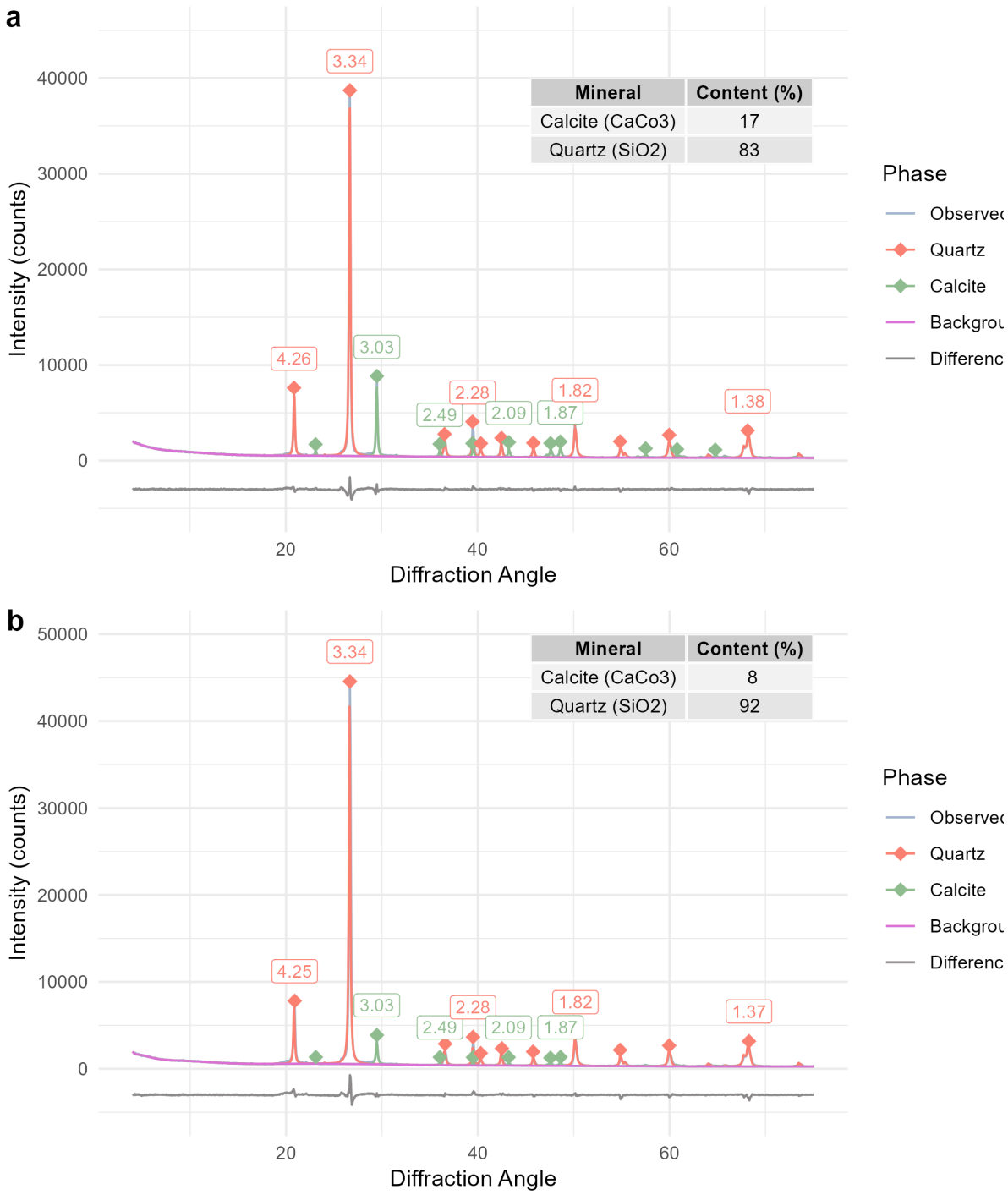

Figure 4.2. Plot of minerals identified through XRD in the a) UJE chert sample from the outcrop Jordana (SP58_JOR) and b) UJW chert sample from the outcrop Praia da Mareta (SP69_MAR). The rhombus shape signifies the main peaks key to identify each mineral. Labels represent the d spacing values of key mineral peaks. Quantifications presented in the supporting table were obtained using Rietveld refinement.

The SEM-EDS results show that all analysed samples are mainly composed of SiO_2. A complete table with all identified elements per sample is available in our online repository (Online resource 5).

Similarly, skeletal remains, represented by calcium and phosphorus peaks and frequently accompanied by small sulphur peaks, occur in samples from all formations and chert types (Figure 4.3). Although frequently without a discernible shape, oval fossils (although currently unidentified) were observed in LJW geological samples and archaeological samples from local cherts (T2 and T4).

This type of large, oval fossil, also composed of calcium, phosphorus and sulphur, seems to be limited to local cherts and specific areas of nodules, characterised by high amounts of these skeletal remains (Figure 4.4).

By observing the surfaces of samples and the presence of skeletal remains, some differences could be noted between local cherts and non-local archaeological samples. In comparison to the frequent to common skeletal remains in the Jurassic cherts from the Algarve, and archaeological cherts attributed to local sources (T2-5), cherts from non-local sources such as T6-8 show little porosity and rare presence of inclusions (Figure 4.5). Whenever present, skeletal remains are small.

The rarity of inclusions is not limited to skeletal remains, but to other inclusions such as oxides, which in T6-8 are small and rare. Despite this difference in abundance and size, oxides are mainly composed of iron, often associated with other elements, possibly suggesting the existence of iron oxide (Fe_2O_3), pyrite (FeS_2) and ilmenite ($FeTiO_3$). Iron oxides were found both as inclusions scattered in the samples, but also frequently associated with skeletal remains, which may be related to their oxidation.

Pyrite was also identified in the shape of spherical pyrite framboids, as well as dispersed pyrite nanocrystals. These are characterised not only by large peaks of iron and associated sulphur, but also by round/angular small nanocrystals organised in spherical shapes, semi-spherical or dispersed crystals, frequently in association with spherical framboids (Figure 4.6). These were present mainly in geological samples from the Upper Jurassic (UJW and UJE) but were barely identified in archaeological samples.

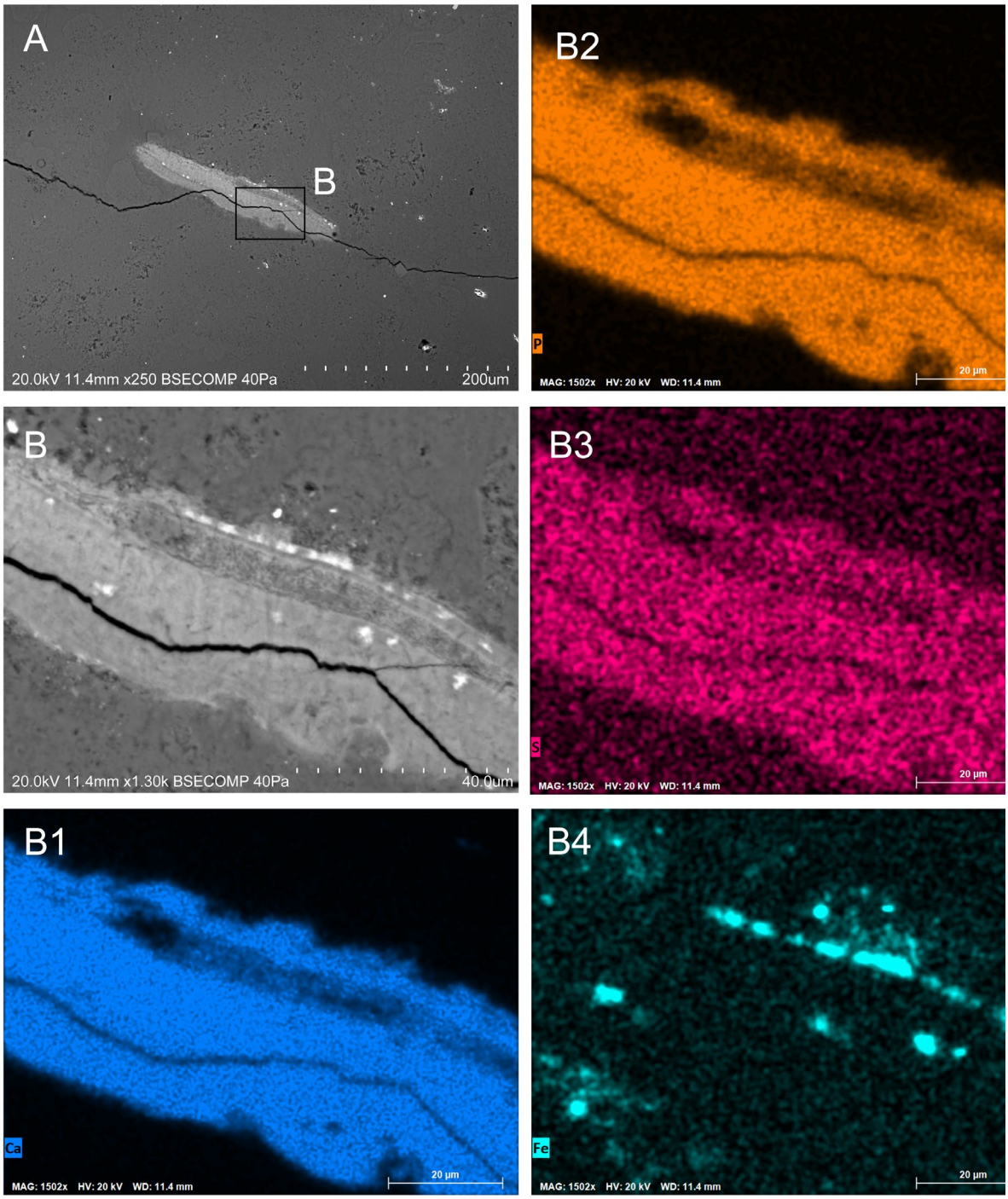

Figure 4.3. A) general view of the sample (x250 magnification) showing a fracture and a skeletal remain. B) detail of skeletal remains (x1.3k magnification) composed of calcium (B1), phosphorus (B2) and a small peak of sulphur (B3). The skeletal remains seem to be oxidised, with small peaks of iron within (B4). Geological sample SP16_BLX from the LJW formation.

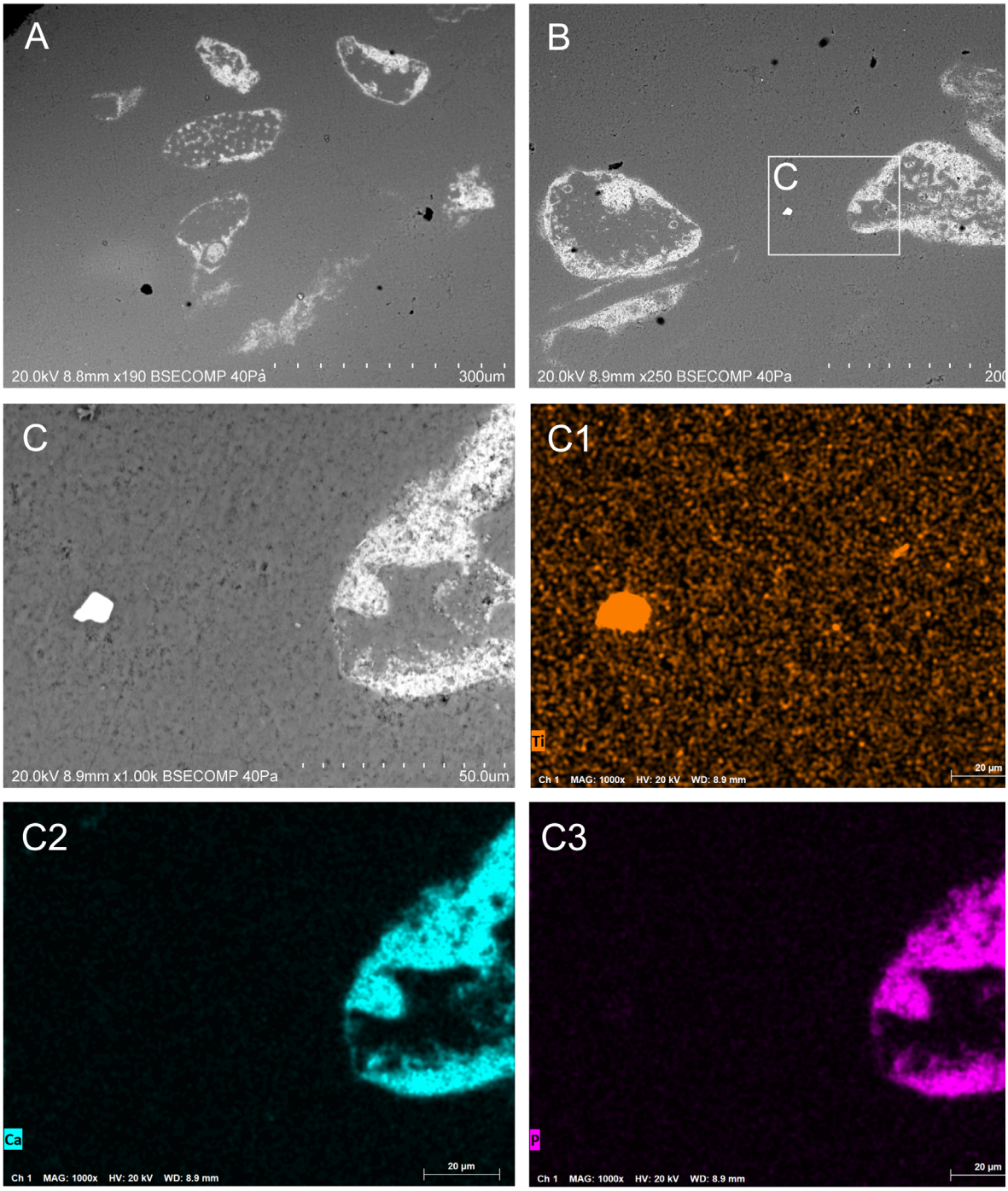

Figure 4.4. A-B) general view of the sample (x190 and x250 magnification, respectively) showing multiple oval fossils and other inclusions. C) detail of an irregular inclusion (x1k magnification) composed of titanium (C1) and an oval skeletal remain composed mainly of calcium (C2), phosphorus (C3) and a small peak of sulphur. Archaeological sample from T4 (H20-4359).

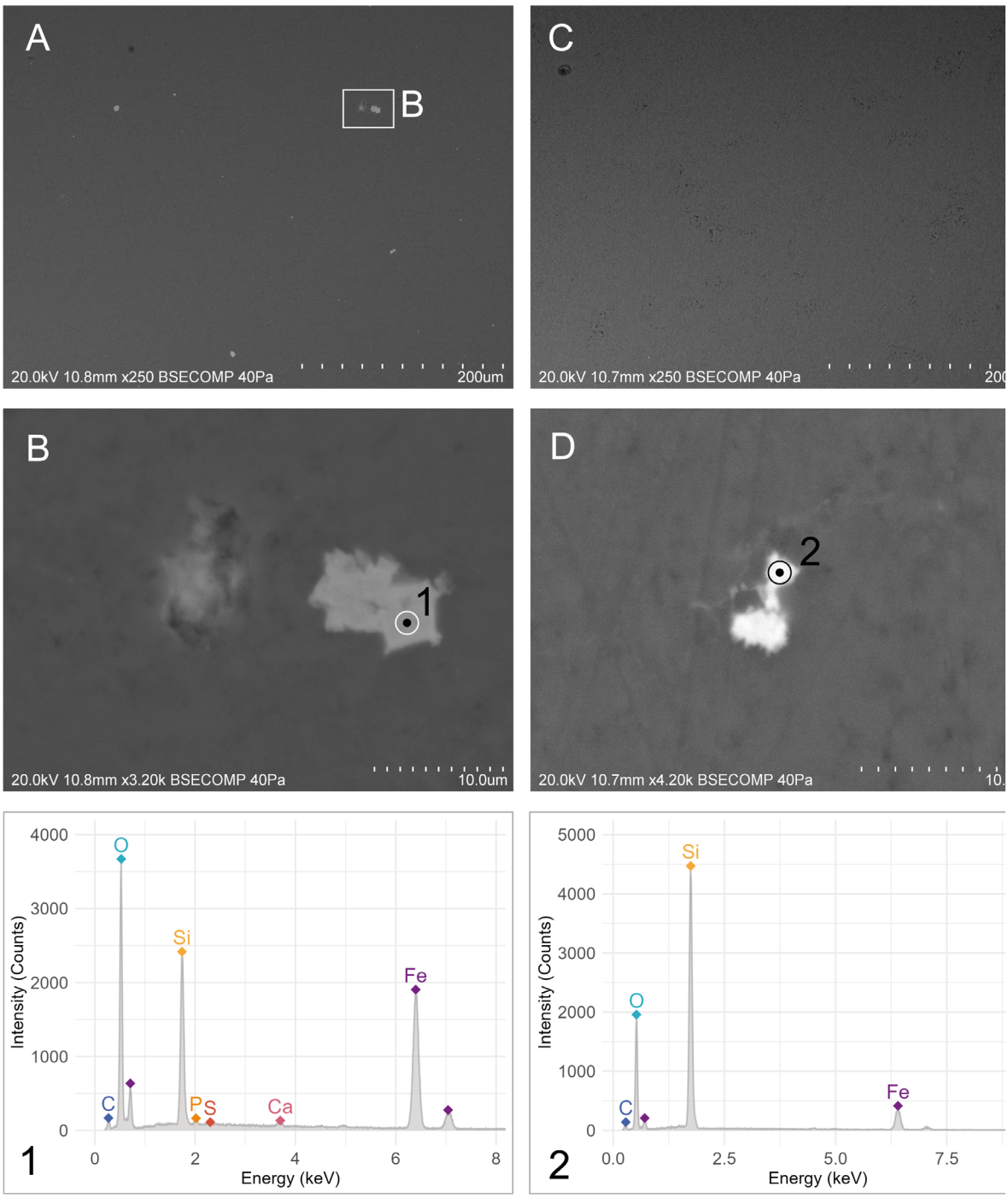

Figure 4.5. A) general view of the sample (x250 magnification). B) detail of an inclusion seen in A (x3.2k magnification), composed mostly of iron and small peaks of calcium and phosphorus, making this inclusion a possible oxidised skeletal remain of a fossil (1). Archaeological sample from T6 (H20-3890). C) general view of the sample (x250 magnification) with no visible inclusions. D) detail of the sample (x4.2k magnification) showing a small and irregular iron inclusion (2). Archaeological sample from T6 (I19-2846). Dot represents the location of the measured spectra plotted in graphs 1-2.

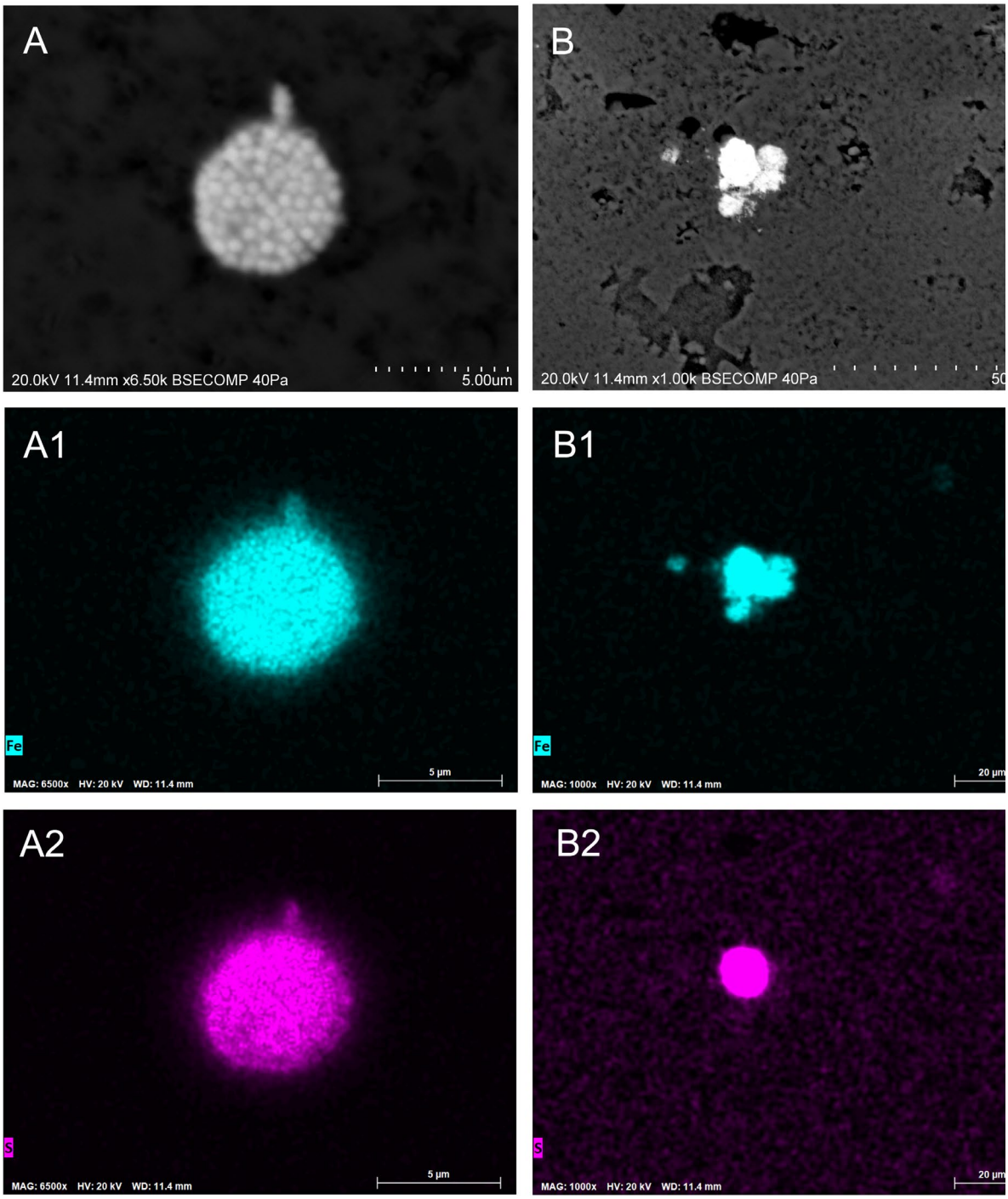

Figure 4.6. A) detail of the sample (x6.5k magnification) showing a possibly spherical pyrite framboid composed of iron (A1) and sulphur (A2). B) detailed view of an inclusion (x1k magnification) composed of iron (B1) and sulphur (B2). Geological sample SP59_JOR_002 from the UJE formation.

In a single sample from LJW and samples from local T4 (both characterised by the previously mentioned oval fossils), inclusions composed of titanium (without associated iron) were identified, which may be related to the presence of rutile (TiO_2). Small peaks of titanium were also identified in 3 out of 4 non-local T6 samples.

Other elements were identified through EDS maps and spectra (e.g., chlorine, potassium or magnesium), although their distribution also showed no patterns between formations and chert types. The exceptions are calcium and aluminium.

Whenever isolated, calcium can be found in high peaks in cherts from Upper Jurassic formations (UJW and UJE) and is probably related to the presence of calcite inclusions (Figure 4.7).

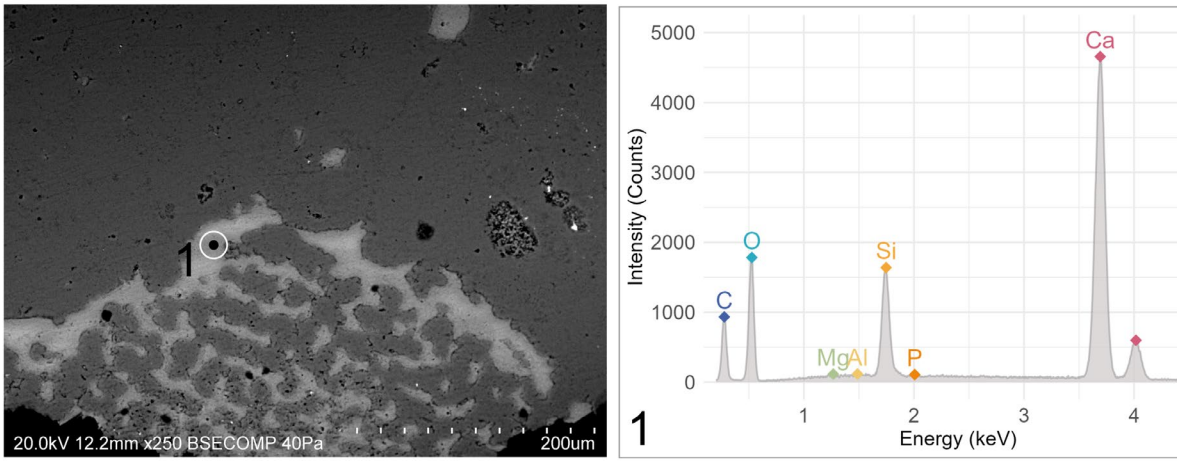

Figure 4.7. General view of calcite inclusions (light grey) composed mainly of calcium and silica (1). Dot represents the location of the measured spectrum plotted in graph 1. Geological sample SP69_MAR from the UJW formation.

Aluminium may be related to the speed of sedimentation; low peaks of aluminium may be related to the fastest sedimentation speeds and may be a useful component to identify differences between cherts. Almost all chert samples show aluminium peaks, although mostly small. An exception is the cherts from the eastern basin of the Algarve (MJE and UJE) and samples from non-local archaeological T7 and T8, which show large peaks. Contrarily, aluminium in both geological samples from the Triassic formations and archaeological group T1 and all archaeological samples from the non-local group T6, with

sources previously attributed to the CPT formation, is either absent or shows negligible peaks.

The pXRF analysis considered 44 major and minor elements, although for a large majority, these were mostly composed of values below the detection level (< LOD) or with values equal to 0. Only elements with more than 50% (n>80) of successful values were maintained in the analysis to allow the successful interpretation of the data (Figure 4.8). This list and a summarised description of the elements and their presence in sedimentary rocks/chert can be found in the supplementary materials (Online resource 3), as well as a table with means, counts and standard deviations of each of these elements and compounds per group (geological formation or archaeological chert type; Online resource 6).

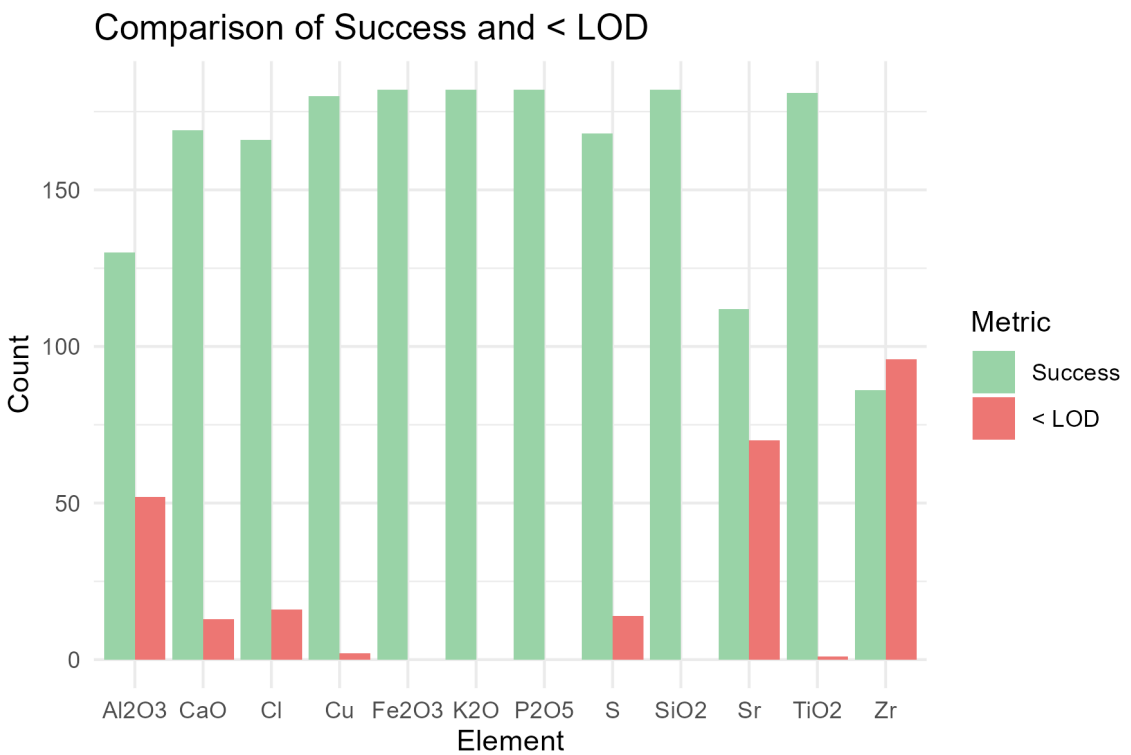

Figure 4.8. Comparison of success (values successfully measured by the pXRF, excluding values of 0 which were non-existent) and < LOD counts of the pXRF analysis by element. Only elements with Success counts above 50% are included.

When focusing on the chosen elements, some patterns become clear; these can be seen as differences in the values between different types of chert, as well as similarities between geological and archaeological samples.

In general, silica is the main component of all cherts. However, there is some variability and outliers in both silica and other elements. From these, LJW cherts seem to show higher variability and more outliers. This may be related to the higher dolomitization process occurring in LJW cherts. Similarly, the lower mean values of silica for UJW samples may be related to high values of calcium oxide (Figure 4.9).

No clear patterns seem to occur between geological groups and archaeological groups, except the CPT samples and non-local archaeological types T6 and T7. This is more marked in Fe_2O_3 (Figure 4.9 c) and, to a lesser degree, in TiO_2 (Figure 4.9 d), which show smaller means and values for these groups. The similarity between these groups can also be seen in the near absence of Sr; where other groups show smaller values but are well represented, the numbers of successfully measured Sr in CPT, T6 and T8 samples are reduced to <50%, meaning Sr (Online resource 6) presence is limited in these cherts. Similarly, CPT and T6 cherts also show less than 50% samples with Zr (Online resource 6), making this element also limited in these chert groups.

Finally, archaeological types T9 to T11 seem to show the most differences in element percentages of all analysed samples; due to the small sample, instead of boxplots (ideally calculated with a minimum sample of 5), the results are shown in Online Resource 6. Albeit with some variation, T9 and T10 show lower percentages of silica in comparison to other samples. As expected, other elements show much higher percentages, especially Fe_2O_3, TiO_2, Al_2O3 and K_2O. T11 shows the lower percentages of silica (~90%; Online resource 6), and, similarly to T9-10 high peaks of Fe_2O_3, TiO_2, K_2O. Compared to all the other samples analysed in this study, T11 shows the highest values for Cu and Zr. However, these are still small percentages within the total chemical composition (<0.0006).

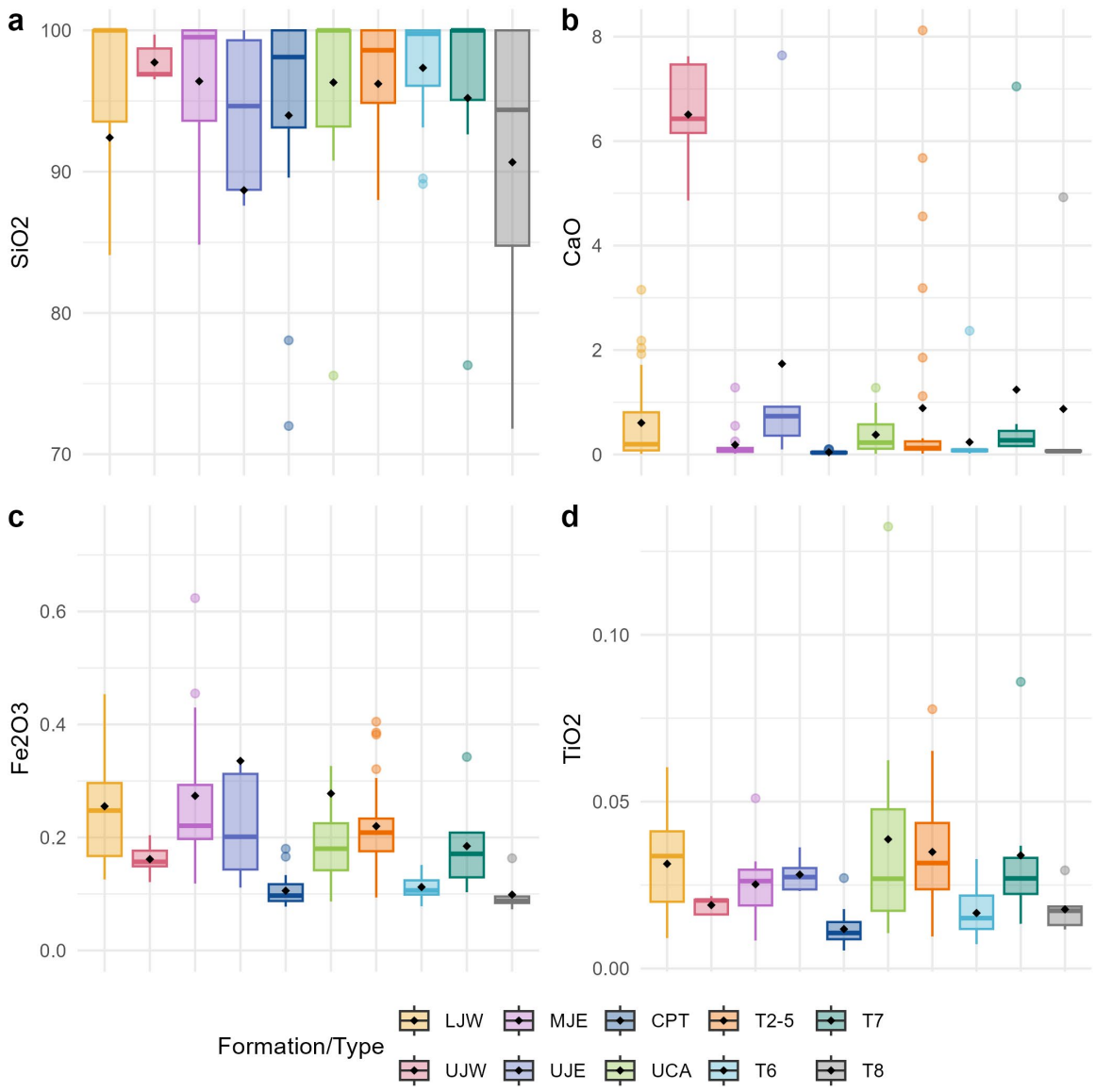

Figure 4.9. Boxplots of raw element percentages (a: SiO2, b: CaO, c: Fe2O3, d: TiO2) by geological formation or archaeological chert type. Only chert groups with n>5 were included in the boxplots. Diamond symbol represents mean values within each group.

Multicomponent statistical analysis was applied to the pXRF results, to understand the relation between the several elements and further identify patterns between the geological and archaeological types. Several PCAs were applied to the elements, however, only a few elements could consistently be used in this approach due to the high percentages of 0 or < LOD. Similarly, small groups (e.g., Triassic and non-local chert types such as T9 and T10) were not included in the PCAs due to the small number of samples.

Figure 4.10 shows the PCAs for several combinations of elements and comparisons between different groups to understand the various relations. The elements used for the PCAs were S, Cl, P_2O_5, Fe_2O_3, TiO_2, K_2O and CaO. In all PCAs the two most representative dimensions are explained by the increased and decreased presence of all elements (Dim1), which may be explained by the increased or decreased values of SiO_2, and the increased presence of CaO, Cl, S and P_2O_5 in comparison to Fe_2O_3, TiO_2 and K_2O (Dim2).

When comparing the regional Algarve cherts (Figure 4.10 a), we see that the first two dimensions explain a combined 60.9% variability in the results, with dimension 1 explaining 34.6% and dimension 2 explaining 26.3%. By observing the scatterplots, it is noticeable that the LJW cherts are highly variable when compared to the other cherts, with samples which display higher positive values in dimension 1 (Dim1) and dimension 2 (Dim2). However, when focusing on the concentration of LJW results, they seem to fit within the range shown by MJE and UJE cherts. In comparison, UJW cherts show higher positive values in dimension 2, which is explained by the higher values of CaO.

The differences between the LJW cherts and non-local cherts are more marked. Figure 4.10 b represents the correlation between elements and LJW, CPT and UCA cherts. Dimension 1 explains ~57% of the variability, while dimension 2 explains ~29%, with a combined percentage of 85.2%. Once again, it is clear that Jurassic cherts, both from southwestern Portugal and southern Spain, show variability, although they are mostly located in the centre/bottom of dimension 2 and centre of dimension 1. When compared to these values, CPT cherts are located in the negative axis of dimension 1 and show little variability.

A similar pattern emerges when applying a PCA using the same elements but comparing them to archaeological, non-local chert T6, previously attributed to central Portugal (Figure 4.10 c). In this PCA, dimension 1 explains ~52% of the variability and dimension 2 ~30%, with a combined percentage of 82.3%. Similarly to geological Cretaceous samples from CPT, T6 samples are also concentrated in the negative side of dimension 1, with a clear overlap between the two.

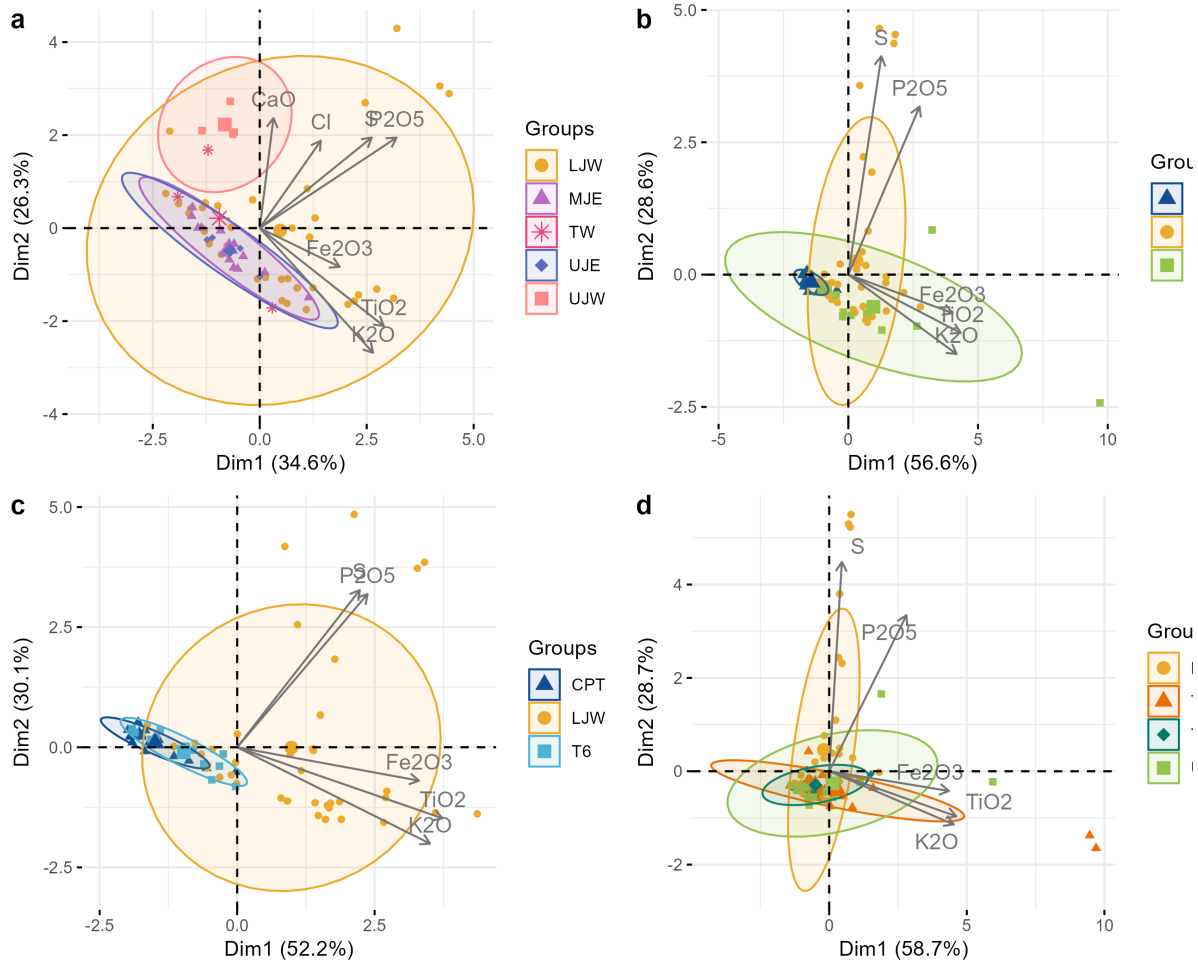

Figure 4.10. Visual representations of dimension 1 and 2 of PCAs showing the correlation between elements and different chert groups. a) PCA using the geological cherts of the regional southern Portugal formations: Lower Jurassic west (LJW), Triassic west (TW), Upper Jurassic west (UPW), Middle Jurassic east (MJE) and Upper Jurassic east (UJE); b) PCA using geological samples of local Lower Jurassic cherts (LJW) and non-local Cretaceous cherts (central Portugal; CPT) and Upper Jurassic cherts (Betic Systems; UCA); c) PCA using geological samples of local Lower Jurassic cherts (LJW), geological chert samples from Cretaceous central Portugal formations (CPT), and archaeological samples from Vale Boi attributed to CPT sources (T6); d) PCA using geological samples of local Lower Jurassic cherts (LJW), geological chert samples from Upper Jurassic southern Spain formations (UCA), and archaeological samples from Vale Boi attributed to local sources (T2-5) and non-local, southern Spain sources (T7).

Figure 4.10 d shows a concentration of all groups in the centre/bottom of dimension 2 (28.7%) and centre of dimension 1 (58.7%), with the first two dimensions explaining a combined percentage of 87.4% of the variability. The archaeological local cherts T2 to T5 and non-local type T7 (previously attributed to the Upper Jurassic cherts of southern Spain) are congruent with the corresponding geological sources, although with clear decreased variability.

4.4 Discussion

The results from this study reveal several patterns in the mineral and chemical composition of the analysed chert samples. In general, they allowed us to answer and explore the several research questions presented above and complete our interpretations about human behaviours related to mobility and raw material procurement and selection. All methods used in this chapter contributed to a more complete characterisation of the geological cherts from the Algarve region, complementing the petrographic analysis, showing key differences in their mineral and chemical compositions.

For example, the presence of calcite in Upper Jurassic cherts (both eastern and western), seen both in XRD but also SEM-EDS and pXRF provided an added characterisation which may prove useful for future archaeological chert raw material studies. This is especially relevant for SEM and pXRF methods, which can be used with little to no impact on the archaeological materials and possibly help distinguish between the visual similarities of regional cherts.

This is especially relevant for the overall goal of providing a detailed lithotheque, both physical and online. By expanding the previously used methods to characterise these geological cherts, we have provided a key reference collection of the Algarve region which can, from this point onwards, be consistently used in archaeological studies for prehistoric assemblages across Iberia.

However, despite the added layers of mineral and chemical characterisation to these cherts, one of the main research questions for this paper and regional research remains unanswered. As previously mentioned, one of the goals of this research was to test the potential of several methods to distinguish between the cherts from the LJW and MJE formations.

Perhaps one of the main differences between the cherts from these two formations is related to the presence of dolomite. The nodules of LJW show small peaks of dolomite in the XRD results. This was expected since a process of dolomitization of the chert nodules, especially on the outer edges, has been identified in previous works (Belmiro et

al., 2023; Ribeiro, 2005), and is related to the formation and diagenesis processes of the geological layers and chert nodules (Ribeiro, 2005; Rocha et al., 1979).

As previously mentioned, however, dolomite is only present in around 60% of the analysed chert samples. This may be related to the size and portion of the nodule selected for powdering, since it is expected that dolomite will be present at the edges of the nodule, closer to the cortex, and can be absent on the inside of a larger nodule. This also may be related to the previously identified heterogeneity in dolomite presence shown in petrographic results or its presence in small percentages within the thin sections (Belmiro et al., 2023). Similar results were identified in previous mineral and geochemical studies, which showed the presence of different degrees of silicification and dolomitization in nodules in the formations (Ribeiro, 2005).

In comparison, the XRD results for MJE cherts show a single sample with small dolomite and calcite presence. This is probably related to the absent or limited dolomitization processes occurring in the Malhão (MJE) formation. This is expected given that the chert nodules are found in limestone formations (Manuppella et al., 2007).

Similarly, elements and compounds like chlorine or calcium oxide are found in higher percentages in LJW cherts (Online resource 6), but with high standard deviations. Silica is, in all analysed groups, the main component of the cherts. However, the LJW group shows a low mean value and high standard deviation (92.4 and 14.7, respectively; Online resource 6), as well as the presence of several outliers (Figure 4.9 a), possibly related to an incomplete process of chertification, as identified in previous geochemical works from LJW cherts (Ribeiro, 2005). In comparison, MJE cherts show a higher silica mean (96.4; Online resource 6) and less variability and outliers regarding other elements and compounds, also seen in the PCA results (Figure 4.10 a).

While this variability seems to be specific to LJW cherts, it is not a key element to distinguish between the cherts of the formations, since a great majority of LJW samples show similar values and characteristics to the UJE cherts. In other words, if dolomitized or chemically variable with high outliers, the cherts are probably from the Lower Jurassic Carixian formation of western Algarve, but if not exhibiting these characteristics, they cannot be ascribed specifically to any of the two.

This means that it is currently still impossible to identify whether chert raw materials are being procured from the eastern Algarve outcrops, and the local LJW cherts continue to be the most probable chert sources being used at Vale Boi during the UP.

Following this interpretation, it is, however, possible to use the presence or absence of dolomite and the chemical variability of archaeological cherts to identify other behaviours related to procurement aside from distance and mobility. The dolomitization process impacts the knapping characteristics of the nodules. This means that there may be the potential for identifying selection behaviours from UP hunter-gatherers focusing on obtaining less dolomitized nodules.

Although the XRD analysis was not applied to archaeological samples, the pXRF results may shed light on this subject. In comparison to the results from LJW cherts, the T2-5 cherts show fewer outliers and variability than their geological counterparts.

This may be related to the process of nodule selection for knapping and the avoidance of the dolomitized cherts with an incomplete process of chertification found in the Lower Jurassic formations. This is also supported by macroscopic observations of the artefacts knapped in the UP assemblages.

Given the previously referred lack of dolomite and lesser chemical variability from the Middle Jurassic Malhão formation cherts, located east of the site, it is also possible that the T2-5 not only reflects the selection of local cherts, but also the procurement of cherts outside of the local range. However, the lack of clear identifiers between the two geological sources and cherts, and following previous interpretations, it is more likely that the disparities between LJW and T2-5 cherts mostly reflect nodule selection during raw material procurement.

The comparison between other archaeological chert types and the geological samples also provided key results to further explore and ascertain previous source attributions.

As established in previous works (Belmiro et al., 2025), the fibrous quartz chert variety from Vale Boi (T1, known as chalcedony) and the cherts from the Triassic formation of the Algarve also showed clear similarities, especially through the SEM photos and EDS spectra.

Similarly, other local types, such as T4, were suggested as not having an exact macroscopic equivalent in the currently known local and regional formations, despite their petrographic similarities. However, the SEM-EDS results showed clear similarities in the visible skeletal remain morphologies between T4, T2 and samples from LJW, and the presence of inclusions composed of titanium in T4 and LJW. This cements the interpretation that, despite the macroscopic variability, T4 cherts are local, possibly from a limited or currently not available outcrop.

Compared to the similar characteristics of local cherts, both geological and archaeological, non-local types showed clearer differences. This allowed us to confirm the interpretation that types T6-11 are not local or regional, although their exact sources cannot be pinpointed.

For example, the pXRF results comparing the chemical composition of local cherts, LJW samples, T7 cherts (previously interpreted as coming from the Betic systems), and samples from the UCA lithotheque showed little differences. In this case, methods such as macroscopy, petrography (Belmiro et al., 2025) and SEM-EDS proved more adequate to show similarities between T7 and cherts of southern Spain.

In comparison, cases like T11 showed clear differences in their chemical compositions, especially in the presence of copper and zirconium, while macroscopically they show no visible fossils or inclusions. These black cherts have been identified in southern Portugal, in the Alentejo region and central Spain (Araújo et al., 2013; Oliveira et al., 1991). Further, studies have discussed the presence of copper mineralisation in cherts from the region (Oliveira et al., 2013). While further studies need to explore this, given the lack of a reference collection for cherts and jaspers from southeastern Portugal and central western Spain, or the inclusion of jasper in this study, we suggest that alike TL01 (Belmiro et al., 2025), T11 may have a source in the Zona Ossa Morena in central Iberia.

The T6 cherts also showed clear differences from the local cherts. The results obtained through SEM-EDS for T6 cherts show a clear absence of inclusions, fossils or porosity, as well as lower to near-absent peaks of aluminium, hinting at different rates of sedimentation (and thus different formation environment) than LJW cherts. Unlike T7

cherts, T6 cherts, when analysed through the PCA, showed a clearer association with CPT geological samples (Figure 4.10 c).

These results show that a multi-layered approach to raw material studies, specifically chert, seems to be key for sourcing studies. While XRD may not be an ideal technique for archaeological artefacts, given its destructive nature and the general homogeneity of chert, other methods provided their contributions to source attribution.

For example, coupled with petrography, SEM-EDS provides a good characterisation for cherts and preliminary chemical composition. The method showed that with little impact on archaeological artefacts, it was possible to further characterise them and establish parallels or differences between archaeological and geological samples. However, it is important to note that for SEM-EDS, the only geological samples used were from the regional Jurassic and Triassic chert-bearing formations of the Algarve. Similarly, this technique was not tested with unpolished samples, possibly posing a difficulty in the identification of some fossils or other inclusions.

A future approach should include added geological samples from cherts of other regions of Iberia, which can be directly compared to the archaeological samples and the use of non-polished samples.

Similarly, pXRF provides a quick and non-destructive technique for the chemical characterisation of cherts, being ideal to complement other methods and results. However, our results showed some limitations of this method. While the PCAs using pXRF results were able to discern between cherts of different ages (Cretaceous and Jurassic), they showed little difference between cherts of the same age but different formations (Jurassic from the Algarve basin and Jurassic from the Betic systems).

As such, pXRF seems to be an ideal method for preliminary studies and characterisations, which can then be complemented with other geochemical techniques, such as LA-ICP-MS or REEs, especially in those contexts where the geological units present very similar siliceous lithologies from a petrological and mineralogical point of view. In this case, a future approach for the geochemical study from Vale Boi would be to apply these methods and compare them to the current results.

4.5 Conclusion

This study highlights the importance of applying a multi-method analytical framework to the characterisation of cherts from the Algarve region. By combining mineralogical and geochemical techniques like XRD, SEM-EDS and pXRF, we were able to refine the characterisation of geological and archaeological cherts and address key questions related to raw material procurement and human mobility during the UP at Vale Boi.

Although some challenges remain—particularly the difficulty of consistently distinguishing between cherts from the Lower Jurassic West (LJW) and Middle Jurassic East (MJE) formations—the integration of mineralogical indicators, such as the presence of dolomite and chemical variability, has opened new avenues for understanding raw material selection strategies.

The results suggest that prehistoric groups engaged in selective procurement behaviours, favouring cherts with better knapping qualities, such as those showing less dolomitization. Furthermore, the use of geochemical methods of both local and non-local cherts within the Vale Boi assemblages and their comparison to samples from other regions strengthens the previous source attributions. This is especially relevant for clearly defining central Portugal as a source for a portion of non-local cherts present in Vale Boi.

The study also underscores the value and limitations of different analytical methods. Techniques such as SEM-EDS and pXRF proved highly effective for an (almost) non-destructive analysis. However, pXRF alone showed limited ability to distinguish between closely related chert formations, highlighting the need for complementary high-precision geochemical techniques in future research.

Finally, this work has contributed to the development of a robust regional lithotheque for the Algarve, providing a critical reference point for future studies of prehistoric lithic assemblages in Iberia.

Future research should expand the geological reference collections beyond the Algarve and incorporate higher-resolution geochemical analyses to further refine raw

material sourcing. In doing so, it will be possible to deepen our understanding of human behavioural adaptations and regional interaction networks during the UP.

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

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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, emphasizing the complex role of lithic resources in mobility, settlement, and social networks.

Keywords: Upper Palaeolithic; Lithic technology; Hunter-gatherer mobility; Chert procurement; Iberian Peninsula

5.1 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 (Gamble et al., 2004; Straus, 1995).

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

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 (Bradtmöller et al., 2012; Morin, 2008; 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., Aubry et al., 2022, 2016; Bicho et al., 2017; Bicho et al., 2011; Bradtmöller et al., 2012; Cascalheira et al., 2021; Cascalheira et al., 2017b; Cascalheira and Bicho, 2013; Finlayson et al., 2006; Gamble et al., 2004; Jennings et al., 2011; Jiménez-Espejo et al., 2007; Linscott et al., 2023; Rasilla et al., 2020;

Schmidt et al., 2012; Zilhão, 2021, 1997; Zilhão et al., 2017). 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 (Gómez and Lunt, 2007; González-Sampériz et al., 2010; Hewitt, 2000; 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., 2017b). 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., 2017b). Its well-preserved stratigraphic continuity allows for a detailed analysis of cultural and technological trends across different phases of the UP.

Building on this significance, research at Vale Boi has provided valuable insights into hunter-gatherer subsistence strategies and technological organisation (Belmiro et al., 2021; Bicho et al., 2017, 2013; Cascalheira, 2019; Horta et al., 2019; Manne et al., 2012; Marreiros et al., 2015; Pereira et al., 2016a), 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 (Bicho et al., 2017; Cascalheira, 2013).

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.

These results, particularly those related to the Gravettian, were interpreted as outcomes of residential mobility rather than direct social network influences, though further investigation is required.

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.

5.1.1 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 (Ambrose and Lorenz, 1990; Binford, 1979; Binford and Stone, 1985; Gould, 1985; Gramly, 1980; Kuhn, 1991; McCall, 2007), occupation types and their duration Kuhn (2004), 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.

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). Whenever raw materials in proximity to a residential site are abundant and of

good quality, a high percentage of formal tools are produced (Andrefsky, 1994; Perlès, 1992), and artefacts show less reduction intensity and decreased conservation through retouching (Thacker and Ellwood, 2002). Whenever local raw materials are scarce or of low quality, non-local resources are procured to produce mostly formal tools (Andrefsky, 1994; Perlès, 1992). Similarly, when groups move to areas where raw material is scarcer or of poorer 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 (Akerman et al., 2002; Brown, 1999; Ericson and Earle, 1982; Oestmo, 2017; Torrence, 1986). 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; Kelly, 1988; Kuhn, 1994; Morrow, 1996; Perlès, 1992; Shott, 1986). In this context, the transport of formal cores (e.g., blade cores) and bifaces used as cores has 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 are also 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; Shott, 1986; Siegel, 1984). 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 (Brown, 1999; Oestmo, 2017; Roth and Dibble, 1998) 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 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). Long-term occupations typically rely on provisioning sites with locally available and suitable raw materials, while non-local materials are gradually used and discarded (Grove et al., 2023; Surovell, 2009). Non-local raw material cores are highly reduced and extensively exploited (Kuhn, 2004; Roth and Dibble, 1998) 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 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 5.1. These expectations are tested through the comparison of local and non-local chert technological and metric characteristics.

Table 5.1. Expected results of the technological and metric comparison between local and non-local cherts.

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

5.2 Materials and methods

5.2.1 Site description

Vale Boi is located on the western coast of the Algarve region, southern Portugal, at a latitude of N 37º5'24.1" and longitude of W 8º48'32.4" (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 (Figure 5.1 a). The site is nestled among limestone outcrops that create west- and southwest-facing rock shelters (Figure 5.1 b). Covering more than 10,000 square meters along the valley slope, Vale Boi includes three main excavated areas, Slope, Terrace, and Shelter (Figure 5.1 c), which were excavated between 2000 and 2019 (Bicho et al., 2013; Bicho et al., 2012, 2007; Cascalheira et al., 2017b; Cascalheira and Bicho, 2013; Manne et al., 2012). 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 primary litho-stratigraphic units were identified. 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, 4C, 4, and Lower 3) between approximately c. 24 and 20 ka cal BP (Belmiro et al., 2021; Cascalheira et al., 2017b, 2013).

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 et al., 2017b; Cascalheira, 2010).

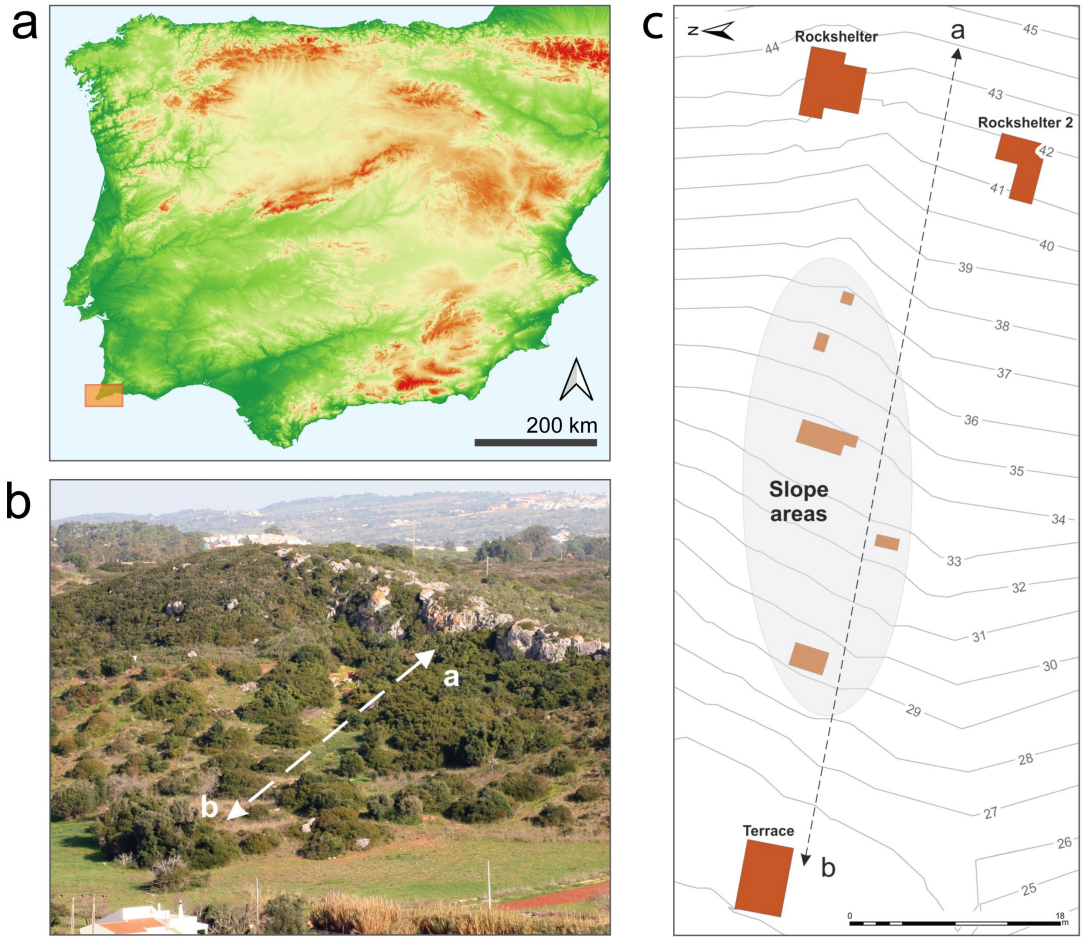

Figure 5.1. a) Location of the archaeological site of Vale Boi (orange box) within the Iberian Peninsula; b) Photo of the limestone hill with terrace and shelter locations; c) Schematic of the site area. Figures b-c) were adapted from Cascalheira et al., 2017. Figure a) was produced with resource to the open-source software QGIS (https://qgis.org/).

The 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 et al., 2013; Cascalheira, 2010) and the Proto-Solutrean assemblages (levels 4E-5) of the Terrace (Belmiro et al., 2021; Belmiro, 2020). 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 (Cascalheira et al., 2013).

The Proto-Solutrean horizons yielded more than 26,500 artifacts (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 (Cascalheira, 2010). Likewise, different raw materials appear to have been used for specific purposes, with chert being particularly associated with the production of a 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). Our previous studies showed, as expected, the existence of local cherts in the assemblages (Figure 5.2 a), originating from the Lower Jurassic (cherts) and Triassic (chalcedony) outcrops in proximity to the site (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).

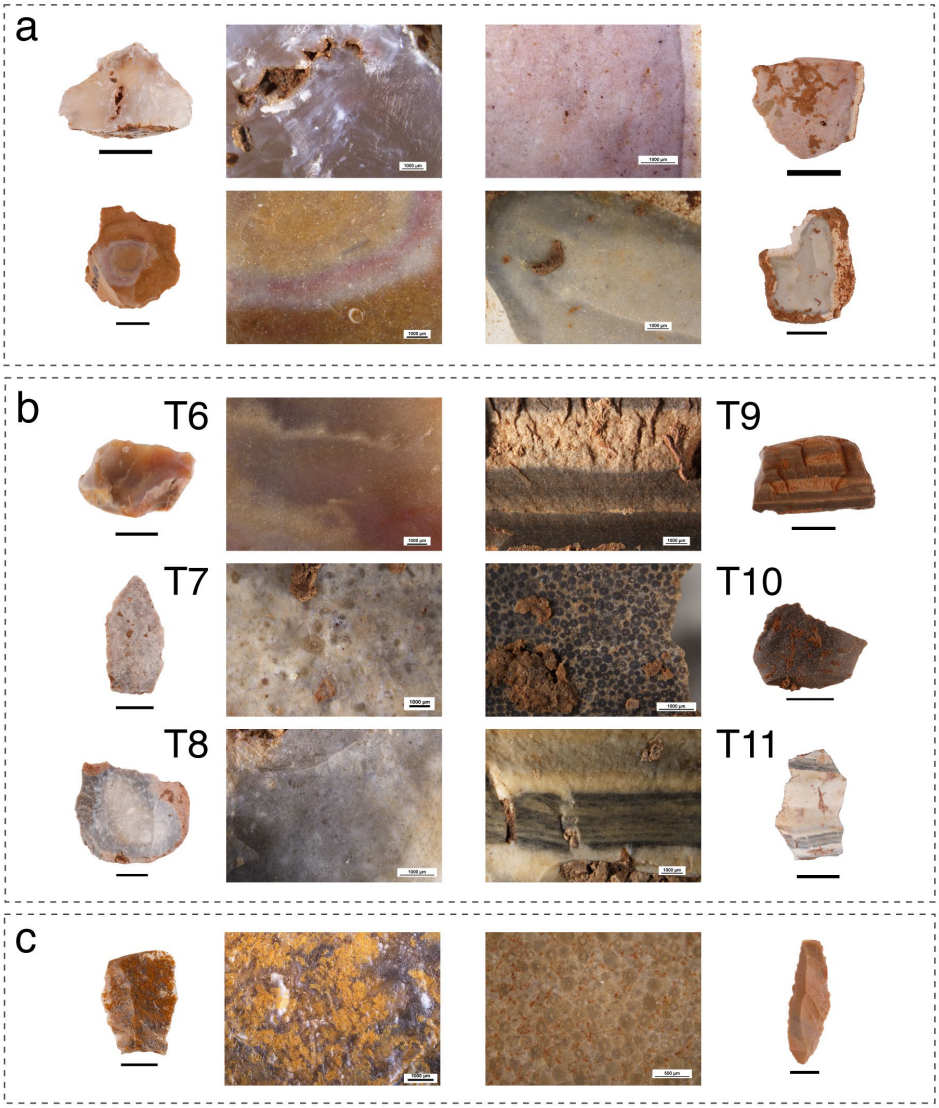

Figure 5.2. Simplified scheme of chert types identified in the UP sequence of the Terrace and Shelter areas of Vale Boi: a) local chert macroscopic variability (T1 to T5), including chalcedony (T1; top left); b) non-local chert types present in all occupations except for T11 which is only present in 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 significant portion of non-local cherts was also identified (Figure 5.2 b-c), with some identified sources, such as the Cretaceous outcrops of central Portugal (Lisbon and Rio Maior areas) and the Upper Jurassic oolitic/peloidal cherts of the Betic Systems in southern Spain. 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. This interpretation is based on high-density lithic assemblages, evidence of tool manufacture, heat-cracked rocks associated with grease rendering, diverse faunal remains (marine and terrestrial), and personal ornaments and portable art (Manne et al., 2012). This is true for most of the UP occupations, although with some exceptions.

Cascalheira et al. (2017) applied the Whole Assemblage Behavioural Index (WABI) (Riel-Salvatore, 2010; Riel-Salvatore and Barton, 2004) to reconstruct and compare mobility strategies at Vale Boi. By analysing lithic volumetric density and retouched tool frequencies from the Shelter's Solutrean (Cascalheira et al., 2013; Cascalheira, 2010) and Magdalenian (Mendonça, 2009) levels, as well as the Terrace's Gravettian levels (Marreiros et al., 2015), the authors confirmed that most occupations corresponded to long-term residential base camps, composed of high-density assemblages with low degree of retouch, except for the Early Gravettian and Magdalenian occupations. 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.

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 (Grove et al., 2023; Surovell, 2009). The high proportions of non-local chert (~50%) in the Gravettian occupations (levels 6 and 7), and gradual reduction in the following occupations, were interpreted as a possible result of settlement changes, where the Gravettian occupations corresponded to short-term occupations, and the other occupations corresponded to residential, long-term occupations with more infrequent moves (Belmiro et al., 2025).

5.2.2 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 were previously collected and published by our team (Belmiro et al., 2025) and can also be found in an online repository (https://www.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 methodology used in the study, the dataset and supporting documents can be found in the article and the online repository.

The Solutrean assemblage technological analysis was published by Cascalheira (2009) as part of a Master's thesis and following publications (e.g., Cascalheira et al., 2013; Cascalheira, 2010), 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.doi.org/10.17605/OSF.IO/UWMPK).

The Solutrean analysis in this study is limited to the Shelter area due to the lack 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.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 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. 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; Cascalheira, 2019; Tostevin, 2012; Zilhão, 1997).

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 a 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.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), 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 5.2). 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.

Table 5.2. 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 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 6-7	781	766

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 5.1), 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 5.3.

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.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 under the MIT

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

Table 5.3. Analysis parameters used in the study, calculation/measurement used for each parameter, and unit of the parameter results after analysis.

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 specialization	N of retouched blanks vs other typologies	N

5.3 Results

Results are structured according to the predefined analytical parameters, comparing local and non-local cherts (Figure 5.2) 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 (Figure 5.3). 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). Albeit in very small numbers in all assemblages (n<10), 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. The presence of knapping by-products such as shatter is also seen in both local and non-local cherts in the Gravettian (Figure 5.3 a) and Proto-Solutrean (Figure 5.3 b) assemblages. Retouched tools are present in all 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.

The Gravettian assemblage exhibits the highest proportion of retouched tools (~21%; Figure 5.3 a), compared to <10% in other assemblages. Tool diversity is greater among non-local cherts, which contain a high frequency of generalised tools (e.g., notches, retouched blanks) alongside hunting implements such as backed bladelets. The abundance of burins and burin spalls suggests they may have functioned as cores, indicating a technological strategy rather than solely a focus on retouch (Online Resource 1 Tables s1 and s3). In comparison to the Gravettian, other assemblages show smaller numbers of retouched tools. 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 (Figure 5.4 a, 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 to 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).

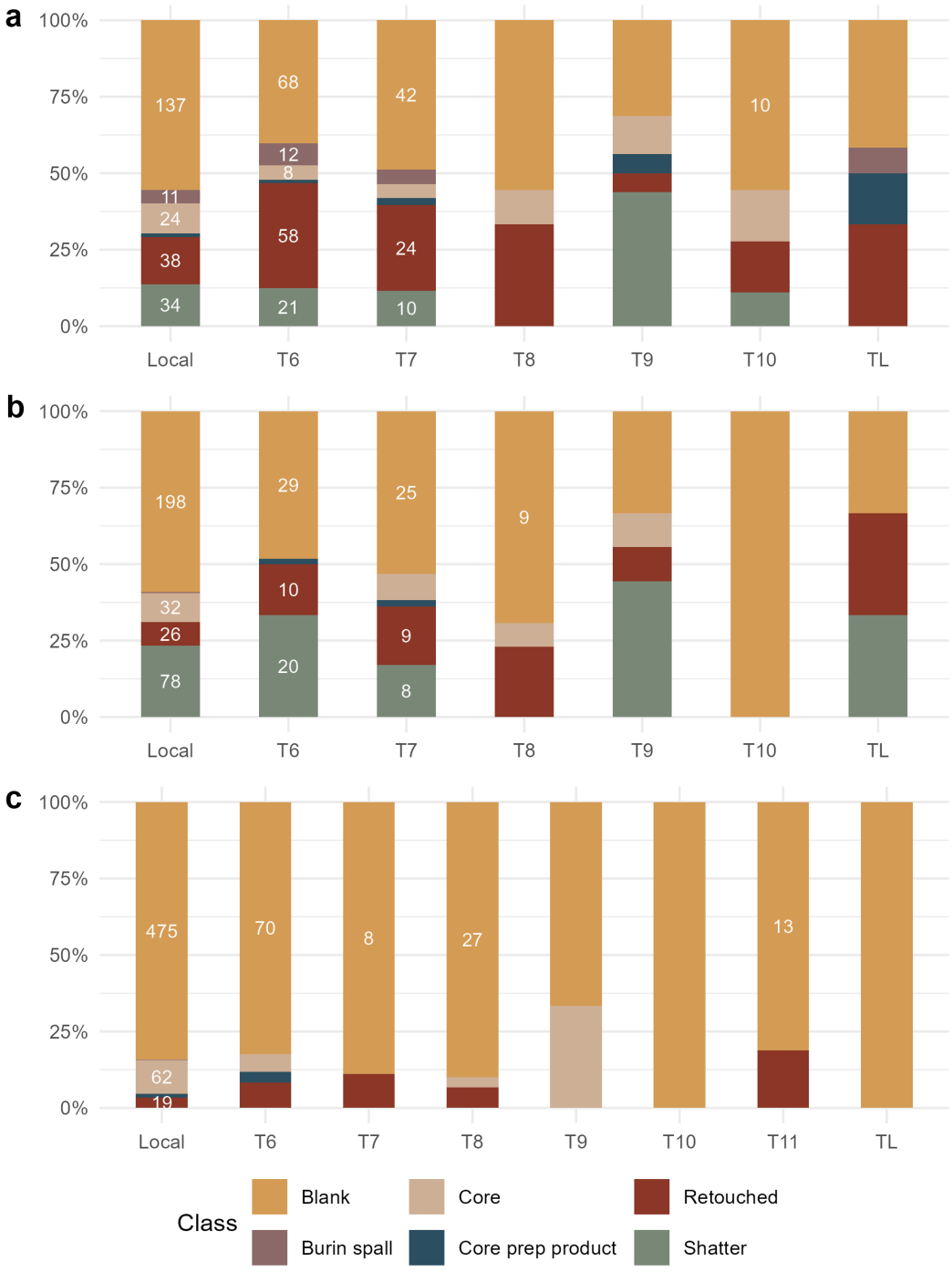

Figure 5.3. Class by chert type in the Gravettian (a), Proto-Solutrean (b) and Solutrean (c) assemblages. Labels within the plots correspond to the number of artefacts within each class. Only labels of n>7 are shown.

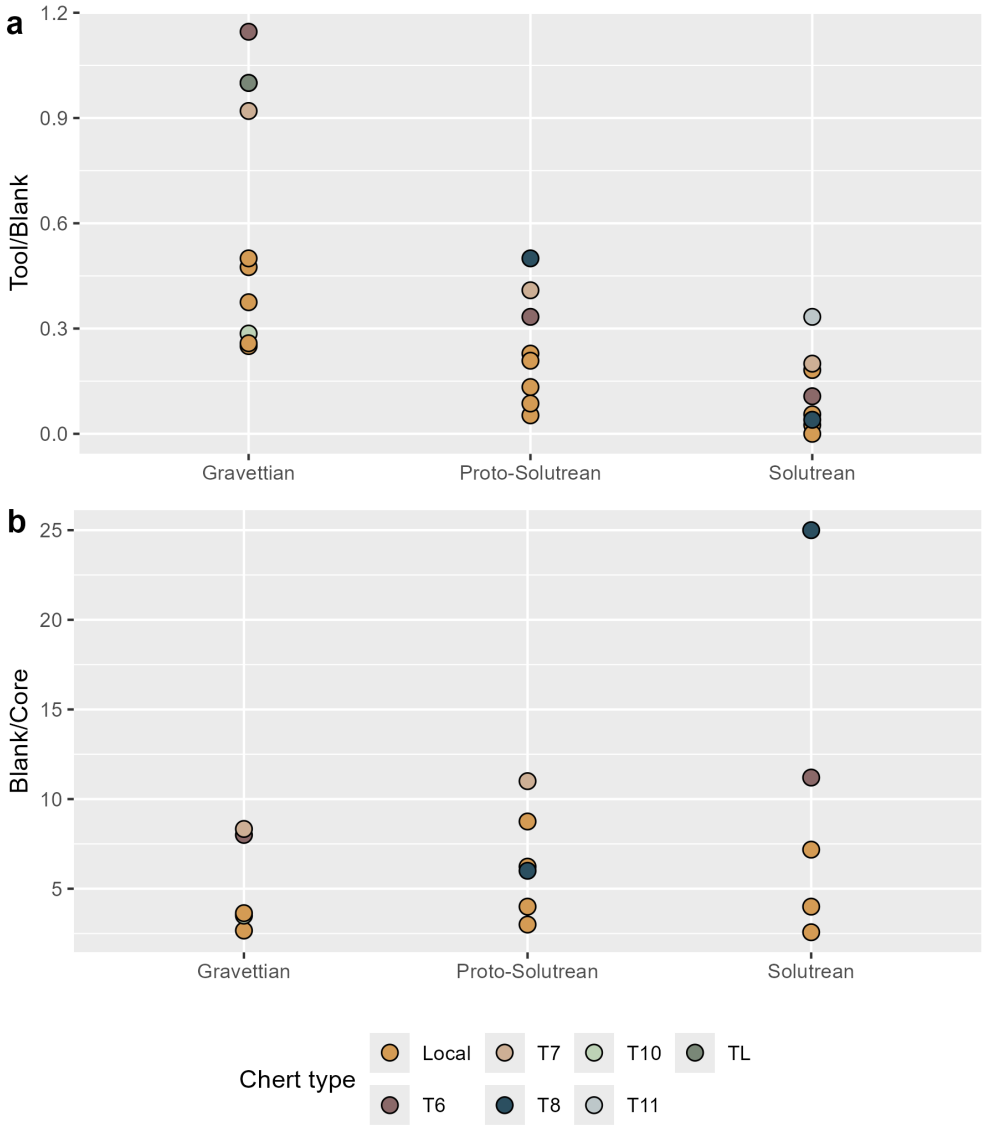

Figure 5.4. Plotted ratios of blanks-to-core (a) and tool-to-debitage (b) by assemblage (Gravettian, Proto-Solutrean and Solutrean) and by chert type. All local cherts were grouped in a single category Local, while non-local cherts maintained their individual types.

Blank-to-core ratios were analysed across assemblages (Figure 5.4 b, 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 T7. However, non-local cores are poorly represented within the assemblage (Figure 5.4 b, Online Resource 1 Table s4).

The sizes of blanks and cores were explored through scatterplots of width and length (Figure 5.5, Figure 5.6, Figure 5.7 a) and boxplots for weight (Figure 5.5, Figure 5.6, Figure 5.7 b) 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 in the several analysed classes. In the Gravettian assemblage (Figure 5.5), non-local chert blanks are significantly smaller than local chert blanks in both length (<25 mm) and weight (<5 g), with p values of 0.00009 and 0.012, respectively. While local chert blanks 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 (Figure 5.6), where length and weight also show statistically significant differences between chert types (0.046 and 0.004), with non-local types showing smaller values. In comparison, in the Solutrean assemblage (Figure 5.7), only non-local chert blank length seems to show statistically significant smaller values (p value of 0.0005) than local chert blanks, being mostly concentrated below ~30 mm, while local chert blank lengths are more variable. While width seems to be more variable in both local and non-local chert blanks, the statistical analysis shows that non-local chert width is significantly higher than local chert blanks (p value of 0.02).

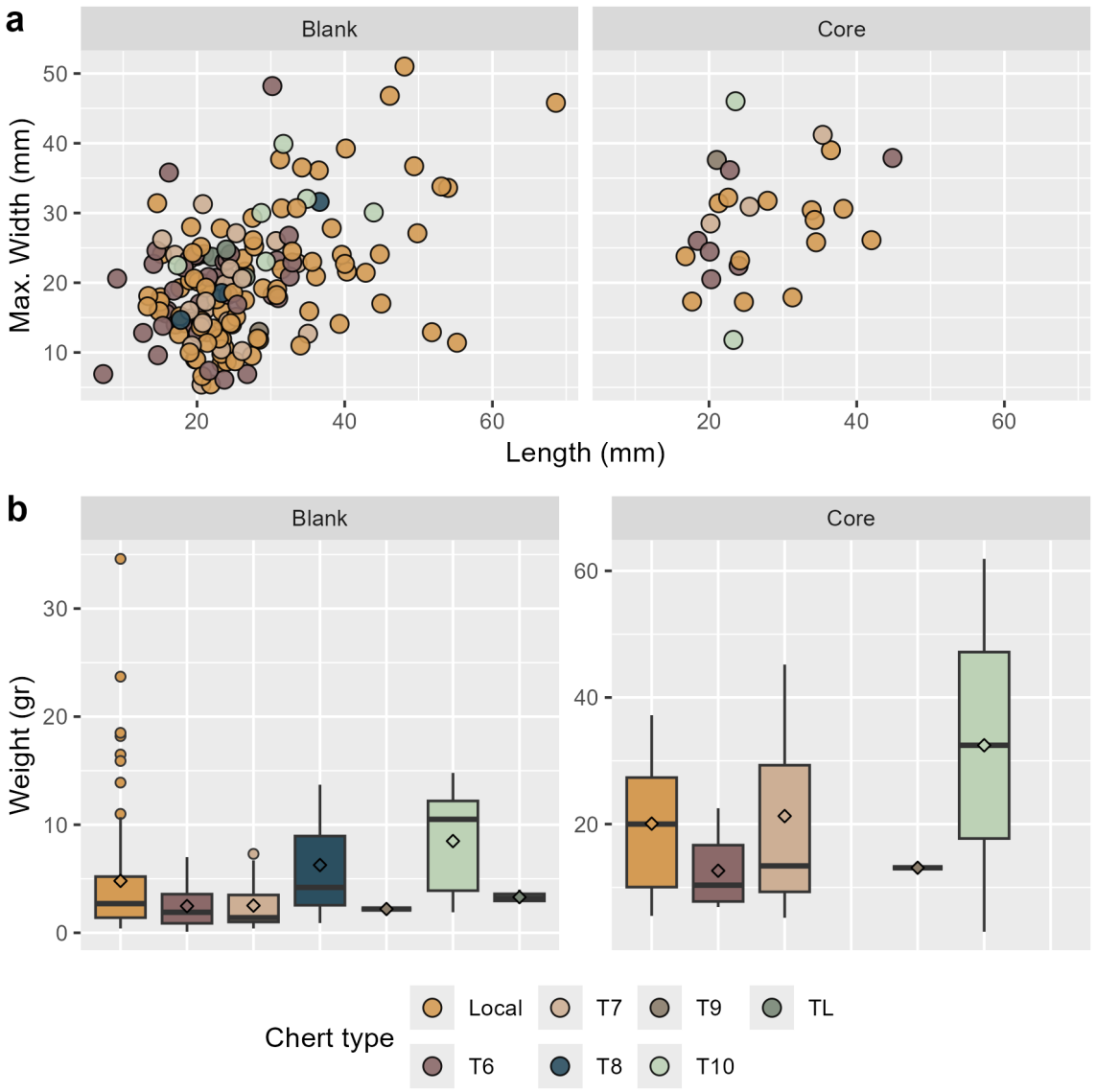

Figure 5.5. Gravettian assemblage blank and core measurements and weight descriptive statistics in local and non-local chert types. a) Scatterplots of width and length. b) Boxplots of weight; diamond symbol represents mean values within each group.

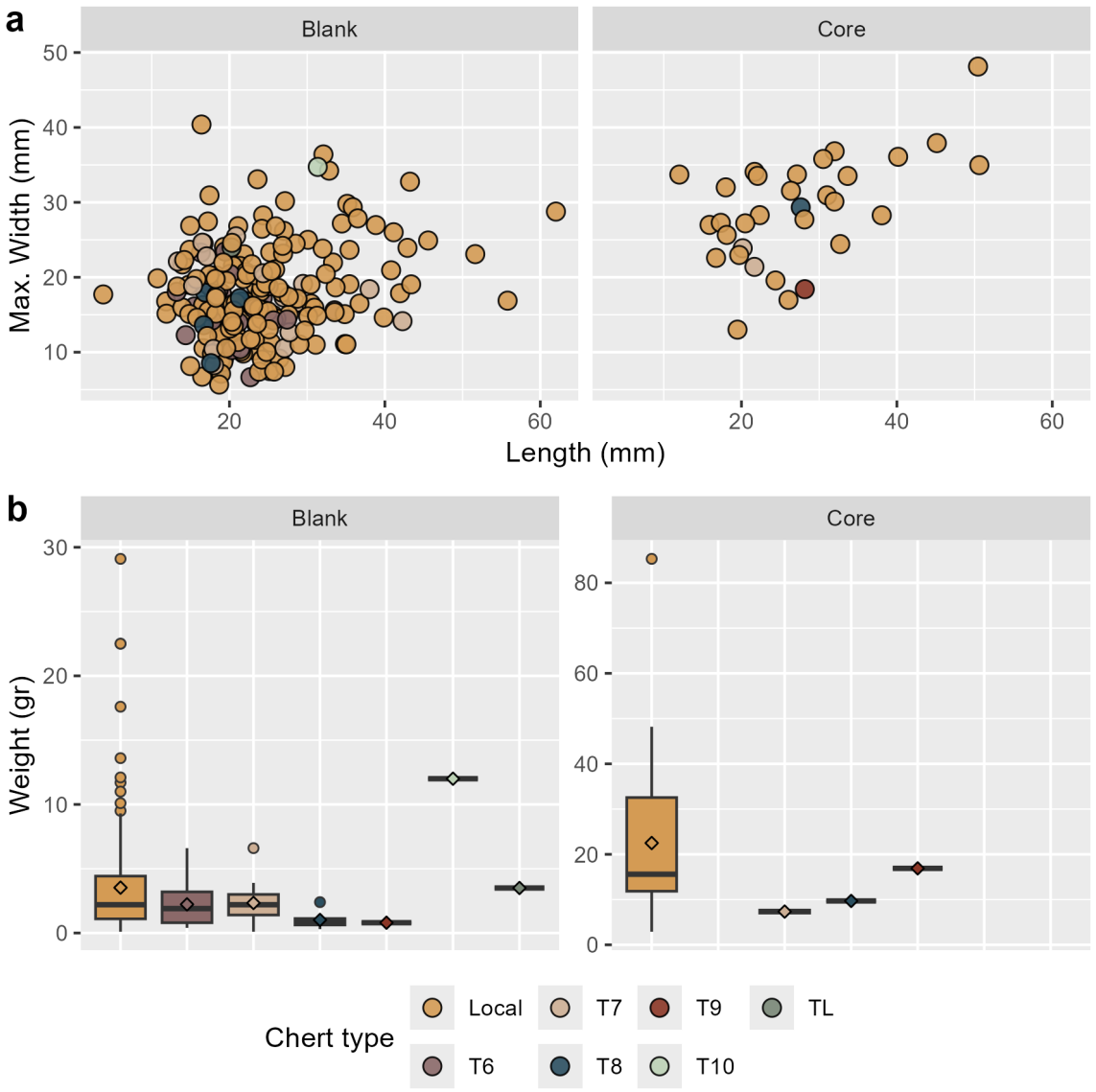

Figure 5.6. Proto-Solutrean assemblage blank and core measurements and weight descriptive statistics in local and non-local chert types. a) Scatterplots of width and length. b) Boxplots of weight; diamond symbol represents mean values within each group.

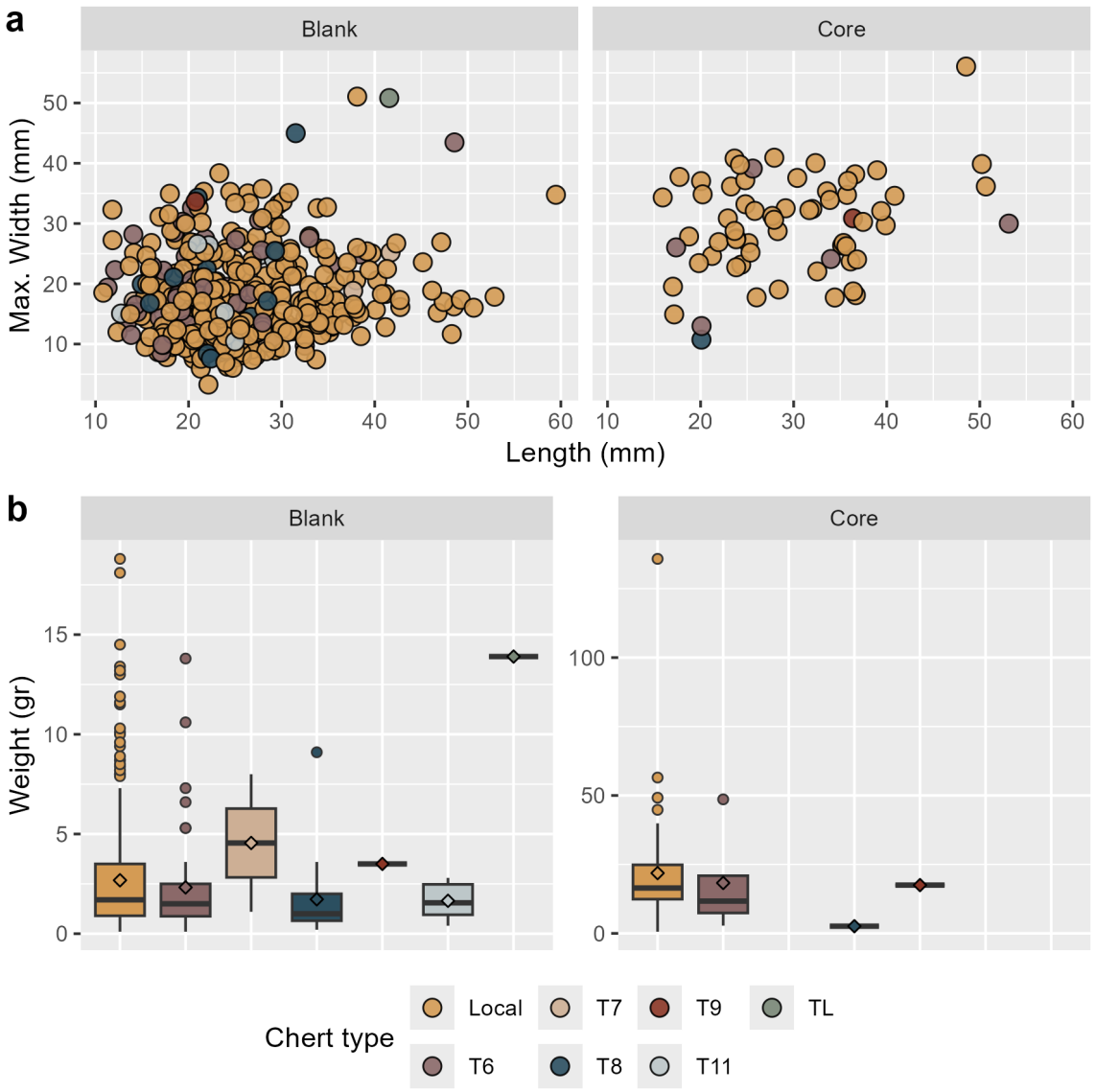

Figure 5.7. Solutrean assemblage blank and core measurements and weight descriptive statistics in local and non-local chert types. a) Scatterplots of width and length. b) Boxplots of weight; diamond symbol represents mean values within each group.

For cores, size and weight differences between local and non-local cherts are less pronounced than those observed in blanks. In the Gravettian assemblage (Figure 5.5), 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. In the Solutrean assemblage (Figure 5.7), 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). 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 ($p > 0.05$). The Proto-Solutrean assemblage (Figure 5.6) 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).

Following the analysis parameters, the results described above can be found in Table 5.4, 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. Tools-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 a high frequency of less specialised tools such as notches and retouched blanks, alongside hunting implements such as backed bladelets (P9). The high frequency of burins seen in this assemblage may be related to their use as cores, representing a knapping strategy more than the presence of retouch.

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. 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 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. Core (P6) sizes show slightly smaller values for T6. Similarly to the Proto-Solutrean, tools-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.

Table 5.4. 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.

	Gravettian		**Proto-Solutrean**		**Solutrean**	
Parameters	**Local**	**Non-local**	**Local**	**Non-local**	**Local**	**Non-local**
P1: Retouched tool %	8.5-17%	~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%	1-2%	-	n=2	1.30%	3.50%
P4: Blank sizes (median)						
a) Width	19.1	17.8	16.8	16.6	16.6*	18.8
b) Length	25.8***	21.2***	23.4**	19.4**	25.1***	21.9***
c) Weight	2.8*	1.9*	2.2*	1.7*	1.7	1.5
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	+	-	+	-	+	-

5.4 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 5.1 a-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; Kuhn, 2004; Roth and Dibble, 1998).

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.

Our results indicate that most non-local cherts were introduced to Vale Boi as cores or nodules, subsequently knapped on-site. However, an exception is 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 blanks, aligning with long-distance individual provisioning models (Kuhn, 2004).

The presence of cores and evidence of on-site knapping enabled a comprehensive 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 underwent 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 blanks. 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 (Grove et al., 2023;

Kuhn, 2004; Roth and Dibble, 1998; Surovell, 2009). However, our results show that these differences are not limited to long-term occupations and low mobility. High blank-to-core ratios and smaller blank sizes in non-local cherts are also observed in the Gravettian occupation, previously interpreted as a short-term occupation with frequent moves (Belmiro et al., 2025; Cascalheira et al., 2017b). 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.

In contrast to blanks, cores exhibited small, though 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 (Andrefsky, 1994; Bamforth, 1986; Kelly, 1988; Kuhn, 2004; Perlès,

1992). 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 idea that non-local raw materials were actively procured, and that greater effort was invested in tool production (Andrefsky, 1994; Kelly, 1988; Perlès, 1992) and the maintenance of existing artefacts through retouch (Kuhn, 2004).

While the high intensity of retouch in non-local cherts aligns with expectations (Table 5.1 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; Shott, 1986; Siegel, 1984). 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. This suggests that these materials were not only transported as unspecialised tools but as volumes that supported on-site tool production and diversification.

While the patterns identified so far have established a clear 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 (Andrefsky, 1994; Kelly, 1988; Perlès, 1992). However, quality may become a less significant factor when non-local raw materials are easily accessible (Akerman et al., 2002; Brown, 1999; Oestmo, 2017; Torrence, 1986). 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, Solutrean bifacial tools and points 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 and less homogeneous composition. 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 (Bachellerie and Schmidt, 2022; Bordes, 1969; Inizan et al., 1976; Tiffagom, 1998).

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 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). 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 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 (Surovell, 2009; Torrence, 1983) 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 southwesternmost 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, 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 (Gómez and Lunt, 2007; González-Sampériz et al., 2010; Hewitt, 2000; 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., 2017b), while still maintaining social interactions and contacts with other groups from Iberia seen both through technological patterns (Belmiro et al., 2021; Cascalheira et al., 2017b; Cascalheira, 2013) 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.

5.5 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.
- Differences between Gravettian, Proto-Solutrean, and Solutrean assemblages indicate shifts in raw material use over time, with the Gravettian phase characterized by higher reliance on non-local cherts, suggesting more frequent

movement or trade connections. In later phases, increased dependence on local resources reflects a shift toward more stable residential occupations.

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.

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6. Discussion

In Chapter 1, we outlined the research questions essential to achieving the overall goals of this doctoral dissertation and project. The answers to these questions collectively provide a detailed picture of how the Upper Palaeolithic (UP) hunter-gatherers of southwestern Iberia obtained and managed their resources, moved across the landscape, and connected with other regions of Iberia, despite their peripheral location.

In this chapter, we address those research questions by integrating and synthesising all the interpretations and conclusions presented in the previous chapters.

What types of cherts were exploited, and how were they introduced into the site?

Throughout the UP sequence at Vale Boi, hunter-gatherers exploited various cherts. Although this research primarily focuses on chert, it is important to note that chert constituted only a portion of the lithic raw materials used at the site (~15-20% from the studied levels of the Terrace area and ~35-50% from the studied levels of the Shelter area; Figure 3.2). Other materials—such as quartz and greywacke—were also intensively exploited, often for specific activities (Cascalheira et al., 2017b; Horta et al., 2019; Pereira et al., 2016a).

A significant amount of cherts used at Vale Boi was local (~45-60% during the Gravettian and up to more than 70% in the following occupations; Figure 3.7), originating from chalcedony and chert formations located inland, within approximately a 10 km radius of the site, or from coastal areas within a 20 km radius (Figure 3.1 b). These materials were brought to the site as nodules, likely collected from primary or sub-primary deposits, and possibly even as clusters of nodules still attached to rock.

No chert from more distant regional sources (e.g., MJE Malhão and UJE Jordana formations >80 km to the east; Figure 3.1 c) was identified in the UP sequence. This

suggests that, despite the broader availability of chert throughout the Algarve region, the hunter-gatherer groups at Vale Boi exploited only a limited portion of the region's lithic resources. Based on current geological and archaeological evidence—as well as indications of coastal resources foraging throughout the UP (Manne and Bicho, 2011)—it appears that the foraging radius of these groups during occupations at Vale Boi was approximately 20 km (foraging range sensu Roebroeks et al., 1988, cited in Brantingham, 2003). Chert procurement was likely embedded within broader foraging strategies (Binford, 1980).

A portion of the cherts used at Vale Boi were non-local (~55-40% during the Gravettian, with a decrease to <30% in the following occupations; Figure 3.7). In most cases, these non-local chert types are consistently present across all occupation levels and areas, excluding T11, which appears only in the Solutrean occupations, and the TL cherts, which are represented by small groups or individual artefacts of distinct macroscopic lithotypes.

At least two different transportation strategies were identified throughout the UP sequence at Vale Boi based on the format in which the products are introduced into the site and the intensity of their use and exploitation there. The majority of non-local cherts appear to have been transported to the site as nodules, partially decortified cores, or larger stone volumes, and subsequently knapped on-site. This is evidenced by the consistent presence of cortex across all non-local chert types—though notably lacking the rounded, pebble-like cortex typical of beach or river sources—as well as by the presence of cores and associated knapping by-products. These findings align with a transportation strategy focused on larger volumes of raw material, as described in other archaeological and ethnographic studies (Clark, 1987; Gould et al., 1971; Kelly, 1988; Kuhn, 1994; Morrow, 1996; Perlès, 1992; Shott, 1986) and are indicative of a site provisioning approach (Kuhn, 2004).

A similar model of long-distance raw material transportation is documented in France, where in the Late Gravettian hunter-gatherers transported complete or minimally pre-formed blocks over distances exceeding 200 km, in preparation for short-term hunting occupations (Delvigne et al., 2019).

By comparison, the Gravettian occupations of the Côa Valley exhibit intermediate long-distance raw material use patterns. Non-local materials arrived as nodules and are found in the archaeological record as reduced cores, core preparation, and maintenance products, indicating on-site knapping. However, imported raw materials also show reduction sequences corresponding only to the final phases of bladelet production and the reuse of blanks (Aubry et al., 2012).

This contrasts with patterns observed at other UP sites across Iberia in relation to long-distance chert procurement. For example, at the Ametzagaina site in the western Pyrenees (Basque Country), non-local raw materials from sources located approximately 50–100 km away are present in Gravettian occupations. These materials are represented mainly by retouched tools and burin spalls, with no associated cores, although core preparation and maintenance tools are present (Arrizabalaga et al., 2014).

This transportation of mainly retouched tools and lack of associated cores shows parallels to the second strategy of long-distance transportation identified at Vale Boi. This is mainly represented in the TL cherts and may reflect provisioning strategies aligned with individual provisioning, as proposed by Kuhn (2004), involving the transport of blanks and tools as part of an individual's portable toolkit.

The presence of these varied types of non-local cherts signals interaction beyond the local catchment, whether through direct travel or down-the-line exchange. While many of the non-local cherts found at Vale Boi currently do not have an identified source, at least three different sources can be surmised from chert types with macroscopic, petrographic and/or chemical similarities to known Iberian sources:

- Cherts from the Cretaceous formations of central Portugal, found near the Lisbon and Rio Maior region (Jordão and Pimentel, 2022; Matias, 2016, 2012), located approximately ~215-250 km north of Vale Boi (as the crow flies; Figure 3.1 a). The attribution is currently based on macroscopic, petrographic and chemical similarities between archaeological and geological samples.

- Cherts from the Upper Jurassic formations of the Betic Systems in southern Spain (Domínguez-Bella et al., 2016; Rodríguez et al., 2011), located over ~250 km east of Vale Boi (as the crow flies; Figure 3.1). The identification is based primarily on

macroscopic traits and petrographic components not found in local or regional cherts.

- Although much less represented, the presence of jasper in the TL chert group and the distinct geochemical signature of T11, as identified through pXRF analysis, suggest these artefacts may originate from the Iberian Pyritic Belt (Araújo et al., 2013; Oliveira et al., 1991), located north of the Algarve region (Figure 3.1). While these resources are not available in primary deposits in the Algarve, they are known to occur in secondary deposits, such as beaches or riverbeds, which could have brought them closer to the site.

In this particular case, the jasper is found without cortex or neocortex, while T11 exhibits a platy-like cortex with an exterior fully altered by post-depositional processes. These characteristics make it difficult to determine the exact method of transportation. However, given the proximity and accessibility of secondary depositional settings—such as beaches or riverbeds—where lithic materials from the Pyritic Belt may be available, it is not possible to confidently infer the type of mobility or transport strategy involved in their acquisition.

As with the regional chert sources absent from the UP sequence at Vale Boi, the limited presence of these jaspers and other cherts in the archaeological record may reflect either their unavailability or inaccessibility during that period, or deliberate choices made by the hunter-gatherers regarding material selection and use.

How frequently did these groups move across the landscape, and can long-distance movements or social contacts be identified through the presence of non-local cherts?

Although long-distance cherts—originating from sources at least 200 km away—were identified at the site (Belmiro et al., 2025), the mechanisms by which they arrived at Vale Boi remain unclear. These materials may have been transported directly by the groups themselves, as part of seasonal mobility patterns, acquired through embedded or direct procurement strategies, or obtained through exchange networks maintained with other hunter-gatherer groups across Iberia.

While the UP occupations at Vale Boi have been interpreted as the result of seasonal mobility, possibly linked to deer and horse hunting activities in spring and early summer (Manne et al., 2012), we do not argue that the presence of cherts from over 200 km away indicates a single cultural group occupying the entire southern half of Iberia. Nor does the evidence support the idea that these materials arrived at the site solely through direct or embedded lithic procurement across such vast distances.

This interpretation is particularly relevant given the distinct directions from which non-local cherts appear to originate. For instance, a round trip between Vale Boi and central Portugal—where Cretaceous cherts were likely sourced—would amount to approximately 500 km. A similar round trip eastward to the Betic Systems of southern Spain would also be around 500 km. Together, these distances highlight the improbability of regular, direct acquisition of such materials over a total range exceeding 1,000 km.

Individually, these residential moves are feasible. Several ethnographic examples document total annual residential movements between 400 and 500 km, such as those of the Mistassini Cree (Rogers, 1963), Tasmanians (Jones, 1974), and Nukak (Politis, 2007). However, such mobility often involves using aids like boats or sledges. In a broader synthesis of hunter-gatherer annual mobility, Kelly (1995) shows that only under extreme environmental conditions—such as those faced by the Baffinland Inuit (Hantzsch, 1977) or the Nunamiut (Binford, 1978)—do residential movements approach the combined distances inferred for Vale Boi when considering the northern and eastern trajectories together.

However, these distances are calculated as straight-line measurements from Vale Boi to the raw material sources, without accounting for topographic or environmental factors. Long-distance movements in those directions may have been shaped by terrain constraints, a factor incorporated into formal models of hunter-gatherer mobility (Brantingham, 2006).

When applied to the Iberian Peninsula, terrain friction mapping demonstrates that travel costs on foot vary significantly from direct distances measured on modern maps (Figure 6.1) (Díaz del Río, 2020). In this context, distance is better understood in terms of travel time rather than absolute spatial measurements (Zilhão, 2021). Díaz del Río (2020) highlights the presence of low-cost corridors—particularly across plateaus and

along the interconnected river valleys of central and southern Iberia, including the Guadalquivir, Guadiana, and Tagus. This suggests that, when compared to other regions of the Iberian Peninsula, these low-cost corridors would have offered much lower friction than other seemingly shorter or same distance paths. Thus, the south-north and west-east movement axis suggested by long-distance raw materials (Figure 6.1) may have been facilitated and preferred due to the low friction of terrain and easier pathways connecting central to southern Iberia.

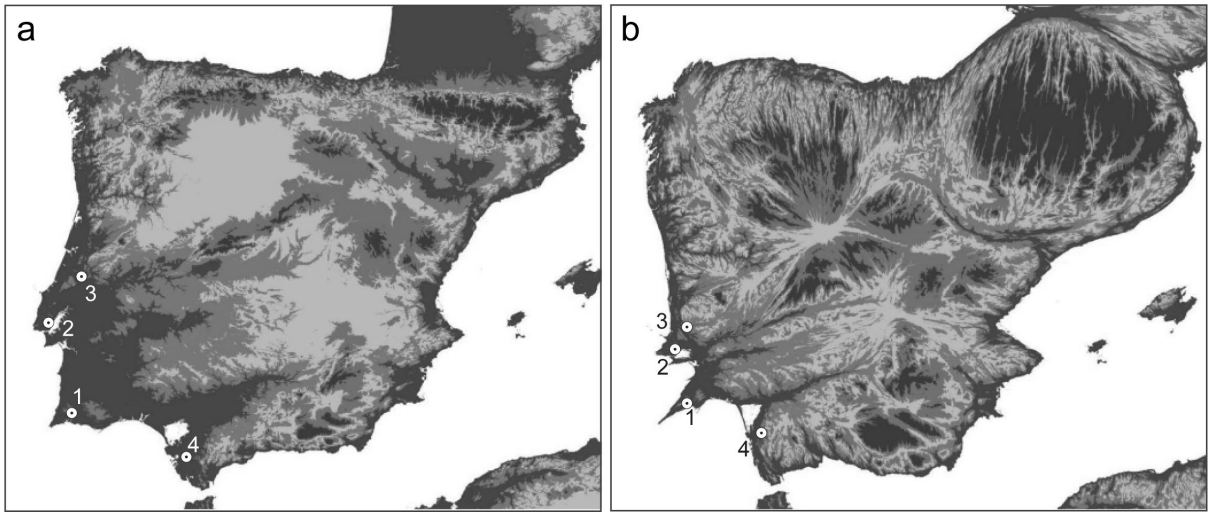

Figure 6.1. Iberian Peninsula map (a) and cartogram (b) showing the comparative costs of moving across Iberia based on the friction of terrain, adapted from Díaz del Río (2020). Dots and numbers were added to the original maps to add reference points in Iberia of importance for the current study: 1) archaeological site of Vale Boi; 2) Lisbon; 3) Rio Maior; 4) Cadiz.

This may also be reflected in other long-distance movements identified in western Europe. In France, archaeological evidence from Gravettian seasonal hunting camps (e.g., Le Blot and Le Rond-de-Saint-Arçon) shows the exclusive use of non-local raw materials, indicating their integration into large mobility circuits within broader territorial ranges (Delvigne et al., 2019).

In this sense, the Gravettian occupations at Vale Boi may be interpreted within a similar framework—as seasonally occupied, short-term occupations used by groups originating from central Portugal and/or southern Spain, who brought with them lithic materials and products.

However, several technological studies of UP lithic assemblages at Vale Boi have revealed key differences in knapping strategies, raw material use, and typology when

compared to assemblages from central Portugal and southern Spain (Marreiros et al., 2015). Vale Boi has often been characterised as a site reflecting resilient behaviours and cultural continuity (Cascalheira et al., 2017b; Manne et al., 2012), but also, particularly during the Gravettian, as exhibiting elements of cultural distinction from neighbouring groups (Marreiros et al., 2015).

While some of these differences may reflect local environmental adaptations or the specific functional characteristics of the site, the distinct typological choices—often linked to style and cultural identity—strongly suggest that the Gravettian hunter-gatherers at Vale Boi constituted a separate cultural group from those in central Portugal and southern Spain. Nevertheless, this cultural distinction does not preclude the possibility of interaction. This scenario aligns with Steward's (1969) concept of broader social networks, or the "maximum band," defining them as a group with which its members (the smaller bands of groups) vaguely identify.

Regarding raw material procurement, while it is not unheard of in ethnographic examples for one group to access the territory of another—often with permission and under established social agreements (Jones, 1974; Kelly, 1995)—distances greater than 200 km for resource acquisition are rarely documented. Ethnographic data generally show that residential mobility seldom exceeds 300 km annually (Kelly, 1995), and that raw materials procured during an occupation are typically sourced within a 20 km radius (Binford, 2001). Materials acquired beyond this range are more often the result of transport from previous locations, rather than direct procurement during a single occupation (Surovell, 2009).

Therefore, it seems unlikely that the presence of distant raw materials at Vale Boi resulted from direct procurement efforts. Instead, their presence more plausibly reflects long-distance transport, whether embedded in seasonal moves or effected through multi-band exchange networks.

Archaeological examples in western Europe document levels of mobility or extensive exchange circuits comparable to those observed at Vale Boi, with many interpretations emphasising the role of social networks connecting hunter-gatherer groups.

For instance, UP sites in the Côa Valley (inland northern Portugal) exhibit patterns of long-distance—or "exotic"—chert acquisition strikingly similar to those at Vale Boi. Spanning the Gravettian to the Magdalenian (though with poorly preserved Solutrean occupations), the Côa Valley sites reveal non-local cherts sourced from the Rio Maior region (southwest; 130–225 km) and the Spanish Northern Meseta (east; 110–205 km). These materials have been interpreted as evidence of inter-group exchanges and the existence of social networks, with contact likely occurring along territorial boundaries during periods of aggregation—a pattern well-documented among hunter-gatherer societies (Aubry et al., 2022, 2016, 2015; Aubry et al., 2012).

This interpretation is further supported by other studies linking sites in southern France (e.g., the Paris Basin) and central Portugal. During the Solutrean and Last Glacial Maximum, these sites show similar raw material procurement and technological patterns over local and regional distances, suggesting a broad interaction network spanning southwestern Iberia and western France—even during periods like the Solutrean, which are poorly represented in the Côa Valley (Aubry et al., 2003).

Additional evidence comes from northern Iberia. At the Valverde site in Galicia, non-local cherts sourced from over 190 km away were identified in Solutrean levels. Although rare, their presence supports the idea that UP groups in Galicia participated in an extensive network of social contacts stretching across northern Iberia and into France (Lombera-Hermida et al., 2016).

Similarly, the Peña Capón site in the Spanish Southern Meseta shows varying percentages of non-local cherts throughout the UP sequence, with the highest quantities during the Solutrean and decreasing presence in earlier periods like the Proto-Solutrean and Gravettian. Macroscopic analysis suggests sources located over 150 km away, interpreted as evidence for contact or mobility between the Tagus and Ebro valleys (Sánchez de la Torre et al., 2023).

Given these parallels, the presence of long-distance raw materials at Vale Boi can plausibly be interpreted as evidence of social interaction—possibly facilitated during seasonal aggregations (Lee, 1972), at the margins of distinct territories (Brantingham, 2006), or within overlapping mating networks (Wobst, 1976), all contributing to the reinforcement of social bonds.

Ethnographic studies further underscore the importance of social networks in explaining long-distance mobility, even when residential mobility remains limited. Long-distance movement often served key adaptive purposes, enabling the formation and maintenance of broader social ties (Gould, 1985). While a minimum band could subsist in relative isolation, multiple bands commonly participated in a larger social network to improve survival prospects and preserve cultural continuity (Wobst, 1974). This pattern may have been especially critical in marginal regions, where social exchange—including mating partnerships, rituals, symbolic systems, and resource trade—was essential for sustaining viable communities (Wobst, 1976).

Ethnographic studies demonstrate that expansive social networks are often developed by hunter-gatherers as adaptive responses to risk, especially in environments characterised by irregular and unpredictable resource availability (Gould, 1978). In such contexts, social relationships serve as mechanisms to mitigate scarcity through information exchange, mutual support, and the circulation of raw materials across vast areas.

For example, ethnographic accounts of !Kung hunter-gatherers show that groups or individuals travelled long distances to gather for winter-gathering, or even for long-distance exchange networks. In their exchanges, goods travelled across hundreds of miles from individual to individual (Lee, 1972). These exchanges were not limited to utilitarian needs but played a vital role in maintaining inter-group ties. Within this framework, the acquisition of exotic goods, including lithic raw materials, can be understood as a byproduct of social cohesion rather than a procurement for its direct purpose (Gould, 1985; Wobst, 1974).

By interpreting the presence of non-local cherts at Vale Boi as the result of exchange and social networks, then we assume the existence of at least two maintained social networks, previously suggested by technological studies (focused mainly on the Proto-Solutrean and Solutrean technocomplexes) (Belmiro et al., 2021; Cascalheira, 2013).

However, the existence of long-distance mobility in hunter-gatherer groups during the UP is, in most cases, expected. Except for situations where specific technological choices may be interpreted as circumstantial responses or ethnographic

and cultural boundaries between different groups, possibly indicating small territories, the very basis of a hunter-gatherer lifeway is marked by mobility and adaptation to the shifts in natural resources and the necessity to respect their renewal times (Kelly, 1995).

Then, by ascertaining that southwestern Iberian hunter-gatherers moved seasonally, moved far, or at least far enough to maintain contact and exchange resources with other groups in Iberia, then there is a key follow-up question: moved how frequently?

Evidence from the site suggests that residential mobility patterns evolved throughout the UP. During the Gravettian, Vale Boi presents archaeological signals of short-term occupations, indicating higher mobility. This correlates with greater frequencies of non-local cherts, particularly those in the TL group, which may reflect either broader ranging mobility or individual provisioning strategies. In contrast, from the Proto-Solutrean onward, Vale Boi transitions into a longer-term residential settlement. Correspondingly, the frequency of non-local lithics declines, with local cherts becoming dominant during the Solutrean, consistent with reduced residential mobility (Grove et al., 2023; Surovell, 2009).

How were different chert types managed by hunter-gatherer groups, and what impact did mobility have on their technological organisation?

These shifts in mobility frequency during the UP not only influenced the quantity of non-local raw materials found at Vale Boi but also shaped the technological and typological characteristics of the lithic assemblages. When focusing specifically on the relationship between occupation duration and technological behaviour, short-term occupations—associated with higher mobility—tend to correspond with increased frequencies of retouched tools, a pattern well-documented in ethnographic and archaeological literature (Grove et al., 2023; Surovell, 2009; Torrence, 1983). The more frequent occurrence of burins, for instance, may reflect an adaptive strategy to mobility, as these tools could serve as cores for the production of bladelets (Barton et al., 1996).

Across all UP phases at Vale Boi, regardless of occupation length, non-local cherts—costlier in terms of acquisition time and transport effort, even when acquired

through exchange—consistently show higher proportions of retouched tools and distinct tool types. This pattern supports interpretations that non-local materials were not only more carefully curated but also reflect a higher investment in production and maintenance, aligning with theoretical expectations surrounding raw material economy (Andrefsky, 1994; Kelly, 1988; Kuhn, 2004; Perlès, 1992).

The types of produced tools show typological diversity, although less specialised tools, such as retouched blanks, remain predominant in non-local cherts across all assemblages. This suggests that these materials were not only transported as unspecialised tools and easily reconfigurable tools (e.g., retouched blanks) as suggested in previous studies (Odell, 1981; Shott, 1986; Siegel, 1984), but as versatile volumes that supported tool specialisation and diversification.

In addition, non-local cherts consistently exhibit higher knapping intensity, indicating an increased effort to maximise their utility once transported to the site. This behaviour conforms to both theoretical models and archaeological expectations regarding the conservation and extended use of high-cost raw materials (Kuhn, 2004; Roth and Dibble, 1998; Surovell, 2009).

This indicates that despite variations in residential mobility throughout the UP, the lithic record at Vale Boi reveals differentiated strategies of raw material management, where distance from source emerges as a key determinant in shaping technological investment and tool use.

How did technological and social organisation evolve over approximately 10,000 years of the UP in southwestern Portugal, and how might climatic changes have influenced these adaptations?

These results indicate a complex pattern of adaptive behaviours across the ~10,000 years of (UP) occupation at Vale Boi, shaped not only by mobility and technological strategies but also by broader climatic shifts. It is clear that both settlement and mobility patterns, as well as aspects of social organisation, evolved over time.

During the Gravettian (c. 30 ka cal BP), Vale Boi was likely occupied seasonally and in short-term occupations, with evidence of high mobility and regular contact with

groups in central Portugal and southern Spain. This period seems to coincide with the onset of Heinrich Event 3 (HE 3), which brought colder, drier conditions. This would be associated with longer-term occupations of ecological niches or refugia within a generally unproductive and patchy landscape regarding resources.

However, it is key to note that the impacts of HE 3 seem to have been milder than other millennial-scale, abrupt climatic events. As such, milder shifts of previous climatic conditions, especially in a Mediterranean region, may not have had a deep impact on resource availability and the landscape.

After the Heinrich stadial, which once again created mild, Mediterranean conditions all throughout Iberia, the onset of the Proto-Solutrean and, subsequently, the Solutrean, coincided with Heinrich Event 2 (HE 2) and the Last Glacial Maximum (LGM) (Belmiro et al., 2021; Cascalheira and Bicho, 2013; González-Sampériz et al., 2010; Schmidt et al., 2012). It is also during this time frame (c. 26 and 20 ka cal BP) (Belmiro et al., 2021; Cascalheira et al., 2017b; Cascalheira and Bicho, 2013) that the settlement patterns and raw material proportions begin to show alterations, after what may have been a small occupational hiatus before the Proto-Solutrean represented by lower frequencies of archaeological materials.

As such, we suggest that as climatic conditions worsened, transforming the southern Iberian landscape from Mediterranean forests to desert-like steppes (Gómez and Lunt, 2007; González-Sampériz et al., 2010; Hewitt, 2000), hunter-gatherer groups continued seasonal mobility, but at a reduced frequency. According to Surovell's (2009) "Mean per Capita Occupation Span" model, this reduction likely stemmed from resource scarcity and the need to avoid overexploitation of ecological niches.

A similar pattern is observed in the UP occupation of the Côa Valley, where from the Proto-Solutrean onwards, the proportions of non-local raw materials decreased with an increased reliance on regional resources in comparison to the Gravettian occupations (Aubry et al., 2012). This may indicate a similar behaviour across Iberia motivated by the occupation of ecological niches.

While it would then be expected that social networks would see themselves expanded during the HE 2 and LGM, given the scarcity of resources, and thus a higher presence of long-distance raw materials on Proto-Solutrean and Solutrean occupations,

the existence of these ecological niches instead possibly fostered an environment of relative stability.

While changes in organisation and behaviour are identified, there are also key elements of resilience throughout the UP at Vale Boi. These are seen especially in the types of raw materials used throughout the UP and their differential use and maintenance. These are elements of the technological organisation of the hunter-gatherers of Vale Boi that show cultural continuity despite the changing technological choices.

The continuous presence of non-local cherts also shows that one possible element of resilience that was established from the first UP occupations of Vale Boi is the reliance on social networks. As such, the social networks established during the Gravettian appear to have persisted throughout the UP sequence at Vale Boi, supporting the notion of stable intergroup ties for at least 10,000 years.

Ethnographic and archaeological parallels further support this interpretation. At Puntutjarpa rock shelter in Australia's western desert, hunter-gatherers continuously occupied the site for over 10,000 years, relying on local lithic sources but maintaining low-frequency access to exotic raw materials (>40 km away) throughout the sequence—clear evidence of a stable long-distance social network (Gould, 1978). In Iberia, the Côa Valley presents a similar case, with a social and resource network extending up to 400 km and maintained throughout the UP (Aubry et al., 2012).

In sum, the patterns of raw material use at Vale Boi—interwoven with changes in settlement duration, tool production, and environmental context—offer a nuanced understanding of UP mobility and social strategies. These findings not only refine previous interpretations of the site but also highlight the resilience and adaptability of the human groups who occupied it.

7. Conclusions and future research

The work presented here strengthens the main interpretations advanced by previous studies and, through high-resolution evidence, casts new light on the Upper Palaeolithic of southwesternmost Iberia—still an underrepresented corner of the European record.

Currently, we have further evidence that there are clear adaptive and resilient behaviours throughout the UP, possibly motivated by changes in the climate, landscapes and resources. Technology changed, following the cultural shifts of western Europe, albeit with regionalisation. Similarly, settlement patterns changed, with the Gravettian (c. 32 and 27 ka cal BP) showing short-term occupations with high frequencies of non-local cherts and retouched tools, and Proto-Solutrean and Solutrean (c. 26 and 20 ka cal BP) showing long-term occupations with lower frequencies of non-local cherts and retouched tools.

Despite these changes, many key aspects of technological and social organisation remained intact. Local and non-local raw material types remain the same throughout all of the UP sequence. In general, all non-local cherts show higher maintenance and intensive knapping in comparison to local cherts. And finally, all long-distance cherts, remains of past social networks, show us that even contacts across Iberia were maintained.

This last element of resilience is particularly important for the understanding of UP mobility in southwestern Portugal, but also the understanding of western Europe UP hunter-gatherer groups and their dynamics. The occurrence of cherts from the Cretaceous formations of central Portugal in archaeological sites, both north (Côa Valley) and south (Algarve) seem to be a common occurrence during the UP and a maintained line of connection. The lines that continuously connect territories between western France, northern and central Spain and central Portugal connect widespread hunter-gatherer groups.

The connection of Vale Boi to southern Spain further expands these long-distance exchanges and social networks across the hinterland and coastal western Europe.

Zooming out of Vale Boi, we may see in western Europe an interconnected web of hunter-gatherer groups, exchanging not only cultural and technological knowledge, but also materials and products, knowledge about resource availability, emphasising the intricate role of mobility in the survival of modern Humans and the key potential of raw materials for tracing these ancient pathways.

Despite successfully answering the research questions, the work on raw materials at Vale Boi is far from over.

The question of which specific local/regional sources were exploited during the UP remains unanswered. This is especially relevant for understanding the foraging range of hunter-gatherers, especially during long-term settlements when movements were infrequent. These possibly also coincided with abrupt climatic events, further impacting mobility patterns. A large portion of chert sources are located within a 20 km radius of Vale Boi, associated with coastal resources and possibly with food resources. Another possible source of chert with similar characteristics (macroscopic, petrographic and geochemical) is located at further distances (>80 km). Identifying the presence of these cherts and their proportions within the identified local types could help us further understand the foraging range of Vale Boi hunter-gatherers, expanding it beyond the immediate coastal niche to the wider Algarve territory.

Similarly, while macroscopic differences allowed the possible identification of non-local cherts (e.g., cherts from the Betic range of southern Spain), pXRF did not allow a further association and distinction between these and local cherts.

These questions could be tackled through the use of alternative analytical methods such as LA-ICP-MS for the in-depth elemental chemical characterisation of cherts and REE analysis (rare earth elements). This method is yet to be tested in the current assemblages and geological samples, but has yielded successful results in other geoarchaeological studies.

Finally, it is key to address perhaps a flagrant caveat or gap about our interpretations—one could say *the deer in the room*. While this dissertation's aim was to

identify patterns in chert use and further characterise the hunter-gatherer behaviour in western Iberia, building upon a larger block of hunter-gatherer groups scattered through the territory, here we researched only Vale Boi.

By approaching a territory as broad as southwesternmost Iberia while using a single site, the results may be truncated by the limited sample size and by the different ways human groups could have organised site use across the landscape.

The UP in western Algarve (and Algarve in general) is not limited to Vale Boi—the territory was occupied by hunter-gatherers, whose presence is signalled in several sites across the region (e.g., Ferrel and Cruz da Pedra) (Zambujo, 1998). These sites, however, are poorly preserved and the lithic collections highly altered by post-depositional processes, decontextualized or unable to be studied—the several analyses conducted in local museums in western Algarve showed that much, providing truncated results that while seemingly showing similar chert types to those seen at Vale Boi, did not allow their inclusion in this study.

Despite this, the existence of these collections provides the opportunity for future studies. Focusing on the existing sites and assemblages in museums from the Algarve, it may be possible to clean, inventory and complete the knowledge of chert use in the region, through dedicated projects and further partnerships with the regional and national institutions. Furthermore, while UP sites are less common, longer-term studies focusing on Middle Palaeolithic to Mesolithic assemblages and sites may further expand our understanding of hunter-gatherer lithic raw material procurement and use trends across prehistory. This is further emphasised by the potential to extend future studies to other lithic raw materials not addressed in the present study, such as quartz, greywacke or dolerite.

The connections between Vale Boi and other regions of Iberia such as south Spain also make it clear that there is potential for the integration of lithic raw material data, not just limited to southern Portugal but expanded to southern Iberia as well. The integration of these studies, along with other resource exploitation, such as animal or plants, from a wider region, may allow us to better define the subsistence and social/economic territories that composed prehistoric southwestern Iberia.

So, while it is true that we cannot fully characterise a whole region and the complex set of human behaviour occurring in that region through 10,000 years by looking at one single site, it is also true that Vale Boi is the only multi-layered, well contextualised, dated and studied UP site in the western Algarve. It is a cornerstone for the knowledge about hunter-gatherer adaptations through the UP and a key puzzle piece for mobility studies across western Europe.

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Appendix A — Repositories and supplementary online materials

All chapters (excluding Introduction and Discussion) have associated online repositories. The materials that would be presented in the dissertation's Appendix section can instead be freely accessed and downloaded through the repositories.

The entirety of the R code used for the analysis, datasets, and visual representations contained in the chapters can be found in their individual repositories. The files include the complete set of raw data used in the analysis, along with the code required to generate all tables and figures, as well as all supplementary materials.

A repository for the full dissertation is also available at https://doi.org/10.17605/OSF.IO/4NYUV. All article and chapter repositories are compiled here for easier and more centralised access. All communications and posters presented in the context of this research can also be found there. Finally, the dissertation is also hosted in this repository in the **Files** section.

In the following sections I present for each chapter its repository DOI (hosted at osf.io). I also present all supplementary materials and a small description, according to their organisation within the original main folder **Files**.

A.1 Creating frames of reference for chert exploitation during the Late Pleistocene in southwesternmost Iberia

See Chapter 2

Online repository: https://doi.org/10.17605/OSF.IO/FP7TA

Files:

../Sample analysis PDFs: Individual analysis documents (outcrop description, macroscopic and petrographic characterisation, stereomicroscope and thin section images) for all samples included in the study. Adapted from analysis document from Spanish National Research Council - Institute Milá y Fontanals of research on Humanities (CSIC).

../SOM/

S1: Field sample/outcrop dataset. Table with recorded data on the outcrops and cherts, during fieldwork and prospections during 2021 and 2022.

S2: Macroscopic analysis dataset. Table with the data collected from the macroscopic analyses of all chert samples collected from the fieldwork and prospections during 2021 and 2022.

S3: Data dictionaries for macroscopic and petrographic analyses. Description of the used variables (including allowed variables and references) for the macroscopic and petrographic analyses used in the present study.

A.2 Within and beyond: chert procurement patterns during the Upper Palaeolithic in southwesternmost Iberia

See Chapter 3

Online repository: https://doi.org/10.17605/OSF.IO/DBFT2

Files:

../SOM/

../Petrographic analysis files: Individual analysis documents (macroscopic and petrographic characterisation, stereomicroscope and thin section images) for all samples included in the study. Adapted from analysis document from Spanish National Research Council - Institute Milá y Fontanals of research on Humanities (CSIC).

../Supplementary Information (SI)/

Online Resource 1: Data dictionaries for macroscopic (group and individual) and petrographic analyses.

Online Resource 2: Terrace and shelter lithotypes complete macroscopic and petrographic description.

Online resource 3: Summarised type macroscopic and petrographic features and epoch/stage identification.

A.3 Within chert: a multi-technique mineral and geochemical approach to the study of chert of southwestern Iberia

See Chapter 4

Online repository: https://doi.org/10.17605/OSF.IO/W78V6

Files:

../Supplementary Online Materials/

Online resource 1: Sample preparation and detailed method description.

Online resource 2: pXRF sample measurements (thickness and min. diameter).

Online resource 3: Chemical elements/compounds and geological implications.

Online resource 4: Supplementary graphs and detailed description of XRD and SEM-EDS results.

Online resource 5: SEM-EDS results by sample. Presence of chemical elements (EDS) and inclusions/fossils (SEM).

Online resource 6: pXRF descriptive statistics table.

A.4 From stone to tool: how raw materials influenced Upper Palaeolithic technology in southwestern Iberia (Vale Boi)

See Chapter 5

Online repository: https://doi.org/10.17605/OSF.IO/UWMPK

Files:

../SI/

Online Resource 1: Supplementary results and tables, supporting information for the results presented in the main paper. Includes detailed assemblage technological descriptions by chert type, tool-to-debitage and blank-to-core ratios tables, descriptive statistics tables for measurements (mean and standard deviation) and results of the Mann-Whitney U statistical analysis.