Tracking the emergence of the Upper Palaeolithic with Multiple Correspondence Analysis of Protoaurignacian and southern Ahmarian lithic assemblages

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Abstract

Reconstructing changes in human behaviour during the Pleistocene, particularly when based on lithic or other artefact types, is often hindered by the traditional categorisation of these materials into discrete entities. The Early Upper Paleolithic of Mediterranean Eurasia – comprising the Protoaurignacian, Early Aurignacian, Northern Ahmarian, and Southern Ahmarian technocomplexes – represents the first emergence of a pan-European cultural unit. However, this conventional categorisation into discrete entities obscures a deeper understanding of the dynamics of *Homo sapiens*' dispersal across Eurasia during this period. In this study, we apply Multiple Correspondence Analysis to assess patterns of reduction processes, technological variability, and inter-assemblage homogeneity across technocomplexes. Using the comprehensive dataset provided in this paper, we analyse variability by grouping it into three key domains: platform preparation, convexity management, and retouch. Solutrean Upper Paleolithic assemblages from the Iberian Peninsula are used as an outgroup. Our results confirm the distinctiveness of Early Upper Paleolithic technologies relative to Solutrean ones. More importantly, they reveal strong technological similarities between the Southern Ahmarian and the Protoaurignacian, particularly in bladelet production—a defining feature of Early Upper Paleolithic technology—and reinforce the role of bladelets as a primary production target. This study aims to establish a foundation for renewed efforts to understand hominin dispersal and interaction during this pivotal phase of prehistory, leveraging open-access databases, standardised protocols and continuous variability analysis in artefact manufacture.

Introduction

The dispersal of *Homo sapiens* in Western Eurasia is a major anthropological topic (Mellars, 2011). The considered period features complex bio-cultural dynamics involving population and material culture replacement, which, albeit occurring almost synchronously at a large scale, also reveal regional developments. Current theories and evidence suggest multiple scenarios (Teyssandier, 2024; Zilhão et al., 2024), with recent research indicating at least two dispersal events of *Homo sapiens*. The first one is dated between 54 – 43 ka and it is now associated with the Initial Upper Palaeolithic, Bachokirian, Bohunician, Lincombian-Ranisian-Jerzmanowician, Uluzzian, and, likely, Neronian (Boaretto et al., 2021; Demidenko et al., 2020; Demidenko and Škrdla, 2023; Douka et al., 2013; Higham et al., 2024; Hublin et al., 2020; Marciani et al., 2020; Mylopotamitaki et al., 2024; Slimak et al., 2022; Tsanova et al., 2024). For some of these technocomplexes, *Homo sapiens* association is evidenced by genetic data, notably the Bachokirian and the Lincombian-Ranisian-Jerzmanowician (Hublin et al., 2020; Mylopotamitaki et al., 2024), and others, the Uluzzian and the Neronian, by teeth morphometrical features (Benazzi et al., 2011; Slimak et al., 2022). In the Levant, the Levantine Initial Upper Palaeolithic is associated with a *Homo sapiens* mandible at Ksar Akil (Bailey and Tryon, 2023) and the technocomplex is linked to the Bohunician by technological resemblance (Demidenko et al., 2020; Skrdla, 2003). We refer collectively to these technocomplexes as Initial Upper Paleolithic (IUP). Another potential IUP assemblage has been published from the hinterlands of Iberia dated at 44.8 -42.9 ka cal BP (Sánchez-Yustos et al., 2024). Nonetheless, IUP technological affinities are also found in Late Mousterian assemblages (Carmignani et al., 2024), pointing to a more complex explanation than simple demic dispersal. Notably, genetic data from the IUP indicates little or no contribution to later Western Eurasian or modern European populations (Hajdinjak et al., 2021; Posth et al., 2023).

The second dispersal is associated with two technocomplexes: the Ahmarian and the Aurignacian (Hublin, 2015). However, while the European Aurignacian is associated with *Homo sapiens* genetically and morphometrically (Bailey and Hublin, 2005; Benazzi et al., 2015; Hajdinjak et al., 2021; Posth et al., 2023; Seguin-Orlando et al., 2014; Svensson et al., 2021), the association between the Levantine Ahmarian and *Homo sapiens* rests upon human remains from Ksar Akil (fossil nickname Egbert) that are now lost (Bergman and Stringer, 1989; Douka et al., 2013).

Throughout the paper, we refer to the Ahmarian and the earlier facies of the Aurignacian (Protoaurignacian and Early Aurignacian) as part of the Early Upper Palaeolithic (EUP). Much of the debate on EUP technocomplexes technology focuses on laminar technology and how this enhanced *Homo sapiens* adaptability (Anderson et al., 2015; Bon, 2002; Kadowaki et al., 2024; Teyssandier et al., 2010). The EUP is roughly comprised within the 43 – 38 ka cal BP, after the IUP and before the advent of the Evolved Aurignacian and Levantine Aurignacian (Alex et al., 2017; Barshay-Szmidt et al., 2018; Marder et al., 2019; Michel, 2010; Shao et al., 2024, 2021). Recent research in the Levant highlights bladelets as the true game-changer (Kadowaki et al., 2024, 2021), suggesting a likely discontinuity between the IUP and the EUP technologies, marked by the widespread production of bladelets believed as projectile points and part of composite tools (Bon, 2005; Chu et al., 2022; Falcucci et al., 2018; Lucas, 1997; Normand et al., 2008; Pelegrin and O'Farrell, 2005).

Lithics are among the most commonly preserved and, consequently, frequently used proxies for human presence and behaviour in prehistoric research (Hussain and Soressi, 2021). They provide a crucial foundation for exploring the geographic spread of similar behaviours. Yet, the traditional practice of attributing stone-tool assemblages to technocomplexes often obscures variability and limits interpretive perspectives. Shea argued for abandoning the naming of stone tool industries — the so-called NASTIES— while Reynolds and Riede compared the European Upper Palaeolithic cultural taxonomy to a "house of cards" (Reynolds and Riede, 2019; Shea, 2014).

Notably, the Southern Ahmarian and Protoaurignacian share techno-typological similarities (Kadowaki et al., 2015; Teyssandier et al., 2010). Recent in-depth technological analysis by one of us has further confirmed a technological similarity between these traditions (Gennai et al., 2021). A recent qualitative analysis suggests that Ksar Akil layers XIII - IX, which exhibit Southern Ahmarian characteristics (Bergman et al., 2017) and are dated to approximately 40 ka cal BP (Bosch et al., 2015; Douka et al., 2013), align closely with the Protoaurignacian (Slimak, 2023). The underlying layers XIX–XVI at Ksar Akil, traditionally attributed to the Northern Ahmarian, are considered closely related to the Châtelperronian (Slimak, 2023). The latter interpretation needs to be carefully evaluated (Djakovic et al., 2024)

However, the reliance on comparing individual attributes, summarising reduction processes into broad narratives, and categorising assemblages into discrete facies or technocomplexes limits our ability to fully capture the variability of human behaviour over time and space. This variability is likely continuous, defying the rigid boundaries of these classifications (Scerri et al., 2014). As Reynolds and Riede observed, improved ways of taxonomical classifications are needed (Reynolds and Riede, 2019). Addressing these limitations is crucial, as traditional methods of analysing lithic assemblages may hinder our ability to reconstruct the dynamics of *Homo sapiens*' migration into Europe and the emergence of widespread cultural phenomena like the Upper Paleolithic.

In this study, we analyse the variability of four lithic assemblages attributed to the Protoaurignacian and Southern Ahmarian technocomplexes, combining technological attributes and examining their variation when grouped into technologically meaningful domains using Multiple Correspondence Analysis (MCA). MCA enables the visualization of relationships and structures among multiple categorical variables by projecting them onto a continuous, orthogonal scale (Abdi and Valentin, 2007). This data-driven approach compares assemblages at the attribute level, with attributes grouped into domains, identifying similarities and patterns on a continuous scale. To ensure robust and reliable results, we focus on large lithic assemblages representing most or all reduction stages. These assemblages span the geographical breadth of the Early Upper Paleolithic (from the Levant to Western Europe) and its rough chronological range (42–38 ka cal BP). We prioritise modern excavations with sieving, which have recovered small-sized artefacts, along with reliable taphonomic reconstructions and radiometric dating. In line with the recommendations of Open Science, we openly share our data and analytical workflow to promote transparency and reproducibility (Marwick, 2019; Marwick et al., 2017; Reynolds and Riede, 2019; Riede et al., 2020; Scerri et al., 2014). By encouraging other researchers to combine their datasets with ours, we aim to enhance the robustness and inter-regional validity of future analyses, following the example set by Cascalheira (Cascalheira, 2019).

Analysis goals and tested hypotheses

We hypothesise that the EUP assemblages we examine will be more similar to one another than to any other Upper Paleolithic assemblages, assuming the distinction of the EUP is valid. To test this, we will compare our EUP assemblages to the closest -in time and space- available dataset: the one published by Cascalheira, which focuses on blade and bladelet production in Solutrean assemblages from the Last Glacial Maximum in Portugal and Spain (Cascalheira, 2019).

Additionally, we hypothesise that assemblages classified as Protoaurignacian will be more similar to one another than to those classified as Southern Ahmarian. If this is not the case, and the two technocomplexes intermingle, it would underscore the limitations of attributing assemblages to these distinct technocomplexes. However, if Protoaurignacian assemblages are indeed more similar to one another, it could suggest an interesting geographic structuring of behaviour, as the Protoaurignacian is considered the first pan-European technocomplex, spreading from France to Bulgaria, while the Southern Ahmarian is regionally confined to the southern Levant. To test this, we will study four sites attributed to these two technocomplexes and located at significant geographic distances from one another: Al-Ansab 1 in Jordan, Româneşţi-Dumbrăviţa I in Romania, Grotta di Fumane in Italy, and Les Cottés in France.

We also aim to test whether the 12 mm width threshold used to distinguish bladelets from blades holds across all assemblages. Ultimately, we seek to evaluate whether the methodology used here can help better understand the homogeneity and regional variability of the Early Upper Palaeolithic.

The different facies of the Early Upper Paleolithic

EUP assemblages are described from sites spanning the Levant, the Caucasus, the Southern Russian Plain, and most of Europe (Fig 1). The study and the definition of EUP technocomplexes have a long history of research (SI file 1). We also provide a comprehensive list of EUP sites considered for the distribution map and a list of radiometric dates obtained with modern methods (SI file 2, 3).

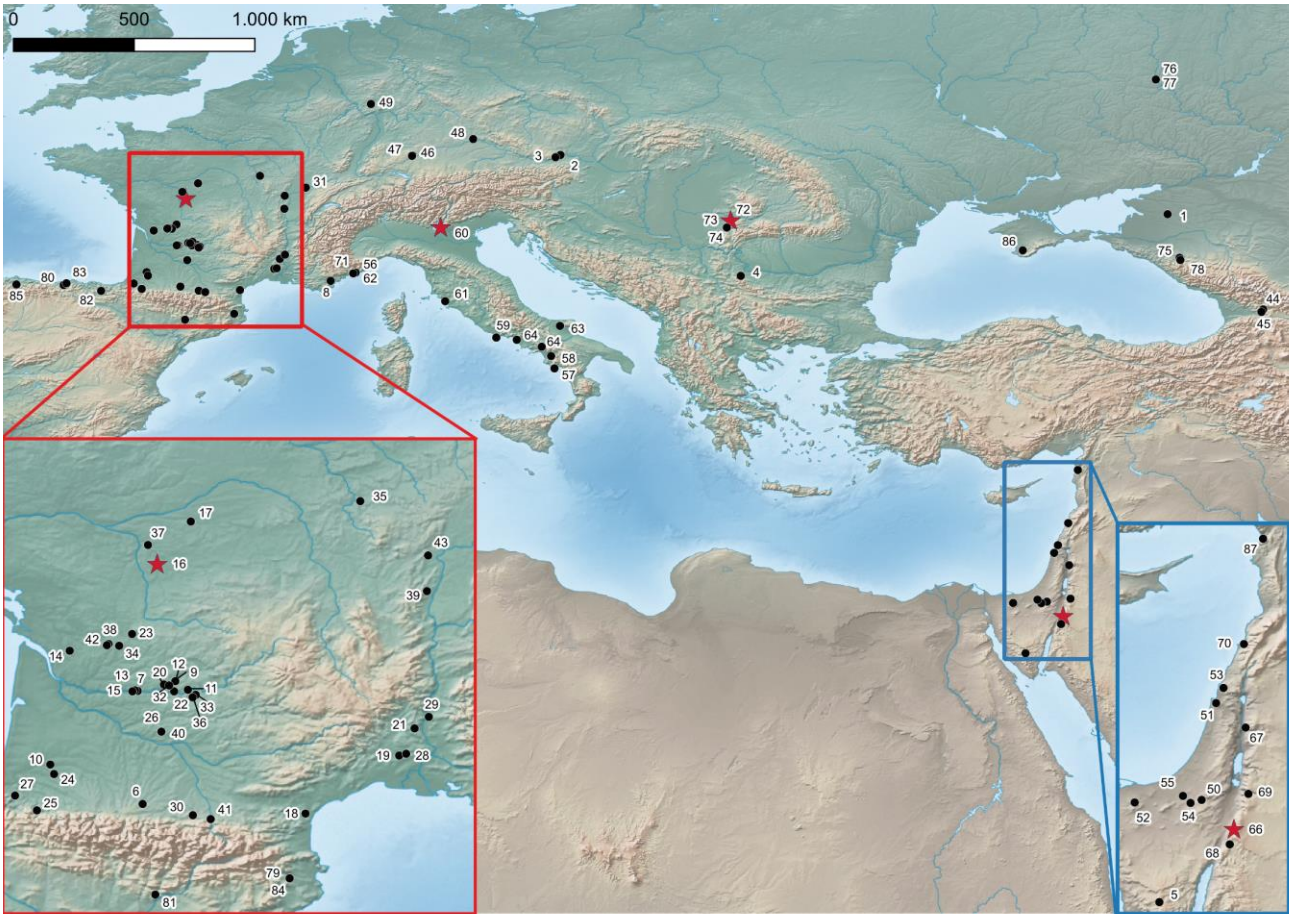

Fig 1. EUP sites*. The stars are corresponding to the sites analysed: 65 – al Ansab 1, 72 – Românești Dumbrăviţa I, 59 – Grotta di Fumane, 15 – Les Cottés. The rest of the sites can be accessed in the SI file 2.*

The Ahmarian is divided into two main *facies* based on technological and metrical features: the Northern Ahmarian and the Southern Ahmarian (Kadowaki et al., 2015). The two *facies* occupy distinct geographical and environmental areas and do not appear within the same stratigraphic sequence (Richter et al., 2020). In the Northern *facies*, there are mostly blade cores exploited with a bidirectional pattern, while in the Southern one cores are exploited with a unidirectional pattern. The Northern *facies* focuses on blades, with rare unidirectional bladelet cores, while the Southern one integrates blade-bladelets in the same reduction or produces just bladelets (Bar-Yosef and Belfer-Cohen, 2019; Gennai et al., 2023; Hussain, 2015; Monigal, 2003). The Aurignacian features an internal variability, that is intensively debated. For the past two decades, the earliest Aurignacian is often portrayed as split into two *facies* or technocomplexes: the Protoaurignacian and the Early Aurignacian. The two *facies* are variously interpreted as chronological phases, as the Protoaurignacian always occurs first in stratigraphical sequences, or adaptations to different ecological niches, being the Protoaurignacian often circum-Mediterranean distributed, while the Early Aurignacian occurs further North or in colder climates (Banks et al., 2013; Bon, 2002). This picture is valid for most of Western Europe (Falcucci et al., 2024a, 2018; Roussel and Soressi, 2013), while elsewhere in Europe discrepancies emerge (Bataille et al., 2018). The Protoaurignacian lithic technology features a continuous reduction of pyramidal, convergent edges, volumetric cores to produce small and slender blades and large and slender bladelets, the latter compose the bulk of retouched implements transformed in variously marginally retouched bladelets and most noticeably the Dufour bladelet sub-type Dufour (Bon, 2002; Bordes, 2006; Falcucci et al., 2018; Laplace, 1966; Roussel and Soressi, 2013; Teyssandier and Zilhão, 2018). The Early Aurignacian lithic technology features a disjointed production of larger blades from prismatic, parallel edges, volumetric cores and small bladelets from carinated cores, in this case, bladelets are rarely retouched (Bon, 2002; Bordes, 2006; Chiotti et al., 2015; Chiotti and Cretin, 2011; Roussel and Soressi, 2013; Teyssandier and Zilhão, 2018).

Radiocarbon dating features a prime spot in the debate and narrative of EUP hominins dispersals and technocomplexes filiation. Despite the Protoaurignacian being generally older and always beneath the Early Aurignacian in stratigraphical sequences, there is a degree of overlapping in the first occurrences of both facies at the continental level (Banks et al., 2013; Barshay-Szmidt et al., 2018; Nigst et al., 2014; Tafelmaier, 2017). Additionally, the dating of Ahmarian contexts suggests a potential overlap between the two *facies* (Boaretto et al., 2021; Bosch et al., 2015; Douka et al., 2013; Phillips and Saca, 2002; Richter et al., 2020; Weinstein, 1984). However, the absence of both facies within the same stratigraphic sequence prevents the determination of their chronological relationship in terms of anteriority and posteriority. The anteriority of the Northern Ahmarian relies on the dates obtained at Manot cave, Kebara cave, and the set of dates obtained at Ksar Akil by Bosch and colleagues (Alex et al., 2017; Bosch et al., 2015; Rebollo et al., 2011). These determinations are either showing a large timespan (Manot cave – (Alex et al., 2017)) or are disputed by other authors (Douka et al., 2015; Zilhão, 2013)

Material & Methods

We will study three assemblages attributed to the Protoaurignacian, excavated at the sites of Româneşti-Dumbrăviţa I in Romania, Grotta di Fumane in Italy, and Les Cottés in France, along with one assemblage attributed to the Southern Ahmarian from Al-Ansab 1 in Jordan. These assemblages have been excavated using modern methods that ensure the recovery of small-sized artefacts, analysed for taphonomy and post-depositional processes, and dated using radiometric techniques. Below we will present the sites and the previous studies and interpretations of the assemblages we will study here.

Presentation of the studied sites

Al-Ansab 1

Al-Ansab 1 (hereafter Ansab) is located in the Lower Wadi Sabra (30°14'2.4″N 35°22'58.8″E; 618 m above sea level) (Richter et al., 2020). Archaeological excavation ran from 2009 to 2020. The archaeological artefacts are embedded in sands and gravels originating from fluvial and aeolian deposits. The site is an open-air location, and the preservation of archaeological features and archaeological artefacts is unaffected by significant post-depositional processes, especially in the northern area of the site (Schoenenberg and Sauer, 2022). Charcoal recovered in AH1 shows that the site was occupied during a brief span between 38 - 37 ka cal BP (Richter et al., 2020; Schoenenberg and Sauer, 2022). The site is excavated using a 1-m^2 basic grid unit, which is further subdivided into quadrants of 0.25 m^2. Layers are geological and are excavated in arbitrary 5-cm-deep spits. Finds ≥ 10 mm in maximum dimension have been individually piece-plotted using a total station since 2015. Finds > 20 mm have two or more points plotted to record the contour. Smaller finds are identified by quadrant and spit number alongside finds retrieved by dry sieving through a 2-mm mesh.

Româneşti-Dumbrăviţa I

Românești-Dumbrăvița I (hereafter Românești) is located on a river terrace overlooking the confluence of the Bega Mare and Bega Mica rivers near the Românești village, in Timiş county, Western Romania portion of the Banat (45°49′2.45″ N, 22°19′15.85″ E, 212 m above sea level) (Chu et al., 2022). The location is open-air with two archaeological *loci* Românești I and II, lying 80 m apart: Românești I is by far the most extensive (Chu et al., 2022; Sitlivy et al., 2012). Faunal and organic remains, in general, are extremely rare due to the preservation conditions (Chu et al., 2022). The first investigations at the site and digging of large portions of the area happened between during the 1960's and the early 1970's (Chu et al., 2022; Sitlivy et al., 2012). A new testpit occurred at the margin of the older trenches in 2009 and it was expanded in 2016, 2018, and 2019 (Chu et al. 2022; Sitlivy et al. 2012). All investigations provided a largely similar stratigraphical sequence featuring the top soil, a layer with Epigravettian lithics (GH 2), a layer with Aurignacian lithics (GH3), and a final layer with few flakes signalling an earlier occupation before the Aurignacian (Chu et al., 2022). Optically stimulated luminescence (OSL) and thermoluminescence (TL) dates bracketed the Aurignacian artefacts to between 42.1 and 39.1 ka, with a mean age of 40.5 ka (Schmidt et al., 2013). The 1 m^2 basic grid unit is further subdivided into quadrants of 0.25 m^2, and digging in these later excavations has proceeded in 2 cm deep spits confined within each geological horizon (Chu et al., 2022). Finds over 5 mm are spatially recorded using a total station, sediments were wet sieved with a 5 mm mesh and selected quadrants with a 2 mm mesh (Chu et al., 2022).

Grotta di Fumane

Fumane is located in the western Monti Lessini Plateau within the Venetian Prealps of northeastern Italy (Peresani, 2022). The site has been continuously excavated since 1982, Fumane is a cave site and it contains a long stratigraphic sequence, spanning from MIS 4 to the Heinrich Event 3, when the cave ceiling eventually collapsed (Peresani, 2022). Macro-unit A includes multiple layers attributed to the Mousterian, Uluzzian, Protoaurignacian, Early Aurignacian, and Early Gravettian (Peresani, 2022). The Protoaurignacian layer A2-A1 date to around 42 and 40 ka cal BP (Higham et al., 2009; Marín-Arroyo et al., 2023). and represent some of the oldest Aurignacian assemblages associated with *Homo sapiens* remains ((Benazzi et al., 2015). These layers predate Heinrich Event 4, as confirmed through the small-mammal assemblage analysis (López-García et al., 2015). Zooarchaeological data suggest that the site was occupied seasonally during late spring and summer, with a focus on exploiting ibex and chamois (Marín-Arroyo et al., 2023). Additionally, the data point to a cold environment, characterised by mostly open landscapes and patchy woodlands. The Protoaurignacian layers are rich in anthropogenic content, with clear combustion features, dumps, and occupation horizons (Marcazzan et al., 2022; Peretto et al., 2004). In addition to the abundant lithic industries, the site is renowned for the discovery of a large marine shell assemblage, indicating the use of ornamental objects sourced at least 400 km away (Peresani et al., 2019). A2-A1 was excavated using a stratigraphic method, with all artefacts larger than 1.5 cm recorded within their respective sub-square meters of provenience (33x33 cm). Both dry and wet sieving of excavated sediments were systematically conducted to recover the smallest organic and inorganic artefacts.

Les Cottés

The site of Les Cottés (46°41'44''N 0°50'40''E ; 90 m above sea level) is located in the Poitou region in central-western France, at the northern limit of the Aquitaine Basin, between the cities of Poitiers and Tours, in the village of Saint-Pierre-de-Maillé (Roussel and Soressi, 2013). The cave opens in a Jurassic limestone cliff, about 30 m high, which dominates the Gartempe river, located nowadays about 150 m to the East. Known since late 19th century, the site has been the object of several excavation campaigns. The interior of the cave was excavated in 1880-1881 (Breuil, 1906; Carthailac, 1881; Rochebrune, 1881). Then the platform at the entrance of the cave was excavated two times in the second half of the 20th century (Lévêque, 1993; Pradel, 1963, 1961, 1959). Between 2006 and 2018, M. Soressi led an update of the stratigraphic and chrono-cultural context based on the sections left by the previous excavators, as well as an extension of the excavated surface (Roussel and Soressi, 2013). A total of 15 m^2 disposed in a U-shape in front of the cave were excavated. Sediment accumulation primarily results from colluvial deposits from the plateau above and erosion of the cliff. All the layers exhibit a regular slope descending towards the South-East. The stratigraphy consists of nine units, six of which contain archaeological assemblages, spanning from at least 43.1 ka cal BP for the Mousterian assemblage (US 08) to 36,400 cal BP for the uppermost Late Aurignacian assemblage (US 02) ((Talamo et al., 2012), calibration on OxCal4.4 using

IntCal20). Single quartz grain OSL and MET-pIRIR dating place the US 08 at 51 ± 3 ka and US 02 at 37.2 ± 1.5 ka (Jacobs et al., 2015). The Protoaurignacian assemblage found in US 04 inférieure is radiocarbon-dated to 40.1-38.9 ka cal BP ((Talamo et al., 2012), calibration on OxCal4.4 using IntCal20). The single quartz grain OSL date of US 04 inférieure, 41 ± 2 ka, is comparable to the radiocarbon one (Jacobs et al., 2015). Archaeozoological data show a progressive evolution of the environmental conditions from a steppic to an arctic landscape (Britton et al., 2023; Frouin et al., 2013). In US 04 inférieure, the disappearance of temperate species indicates colder conditions than those of lower assemblages. The upper part of US 04 (referred to as supérieure), attributed to the Early Aurignacian, is often separated from US 04 inférieure by a thin sterile layer. US 04 inférieure is often separated from the underlying US 06 (attributed to the Châtelperronian) by a 15 cm-thick low-density layer, US 05. A total of 5351 pieces greater than 1,5 cm were analysed. Raw materials mostly come from local sources (Upper Turonian), while about 20% of the pieces come from the Grand Pressigny region (20-40 km to the North) and 5% from more distant areas (over 40 km from the site: (Primault, 2003)).

Previous studies and interpretations of the studied assemblages

The assemblages have been the object of previous independent studies

Al-Ansab AH 1

The assemblage has been studied to retrieve technological behaviours and mobility assessment. The first analyses by Hussain and Parow-Souchon (Hussain, 2015; Parow-Souchon et al., 2021) provided the attribution to the Southern Ahmarian technocomplex. The analysed assemblage consisted of the artefacts retrieved during the 2009 – 2013 excavations campaign that mostly interested an erosional step. Parow-Souchon interprets the assemblage as the result of multiple residential mobility occupations that left a wide range of lithics and a complete reduction sequence due to the undifferentiated activities on site and vicinity of the raw material sources. In 2018 the analysis resumed by one us (J.G.) to contextualise the bladelet production and provide a continental comparison of the EUP technologies. In addition to the 2009 – 2011 coordinated artefacts, the analysed sample comprised coordinated artefacts from squares excavated in the 2018 campaign (Fig 2). Technology at Al-Ansab AH 1 involved a repetitive and standardised scheme. Raw material nodules feature an oblong shape; therefore, the flaking surface is generally placed on the shorter face and reduction progresses frontally. Striking platforms are plain and the knapping angles are very acute, resulting in strong distal convexity. The start of the lamino-lamellar reduction is often placed around natural lateral ridges, which then merge into one single flaking surface. Very few formal bifacial crests are present. At the time of discard, cores show a semicircumferential shape, or they retain the narrow-faced shape. Knapping products are mainly blades and bladelets, as flakes intervene mostly during the earliest phases of the core roughing out and during part of the core flank management. Some of these flakes are then recycled in burin cores. Gennai's interpretation primarily differs from that of Parow-Souchon and Hussain regarding the role of bladelets in the reduction process. While Parow-Souchon and Hussain predominantly interpreted the assemblage as blade-oriented (Parow-Souchon et al., 2021), Gennai considered the abundance of bladelets and their role within the reduction process as evidence that they were the primary focus of production, with blades representing only a minor component. Bladelets-sized negatives are often found on the flat part of the flaking surfaces and encased by lateral blade-sized negatives. Bladelets-sized negatives are often found intercalated with blades and on blades dorsal faces (Gennai et al., 2023, 2021).

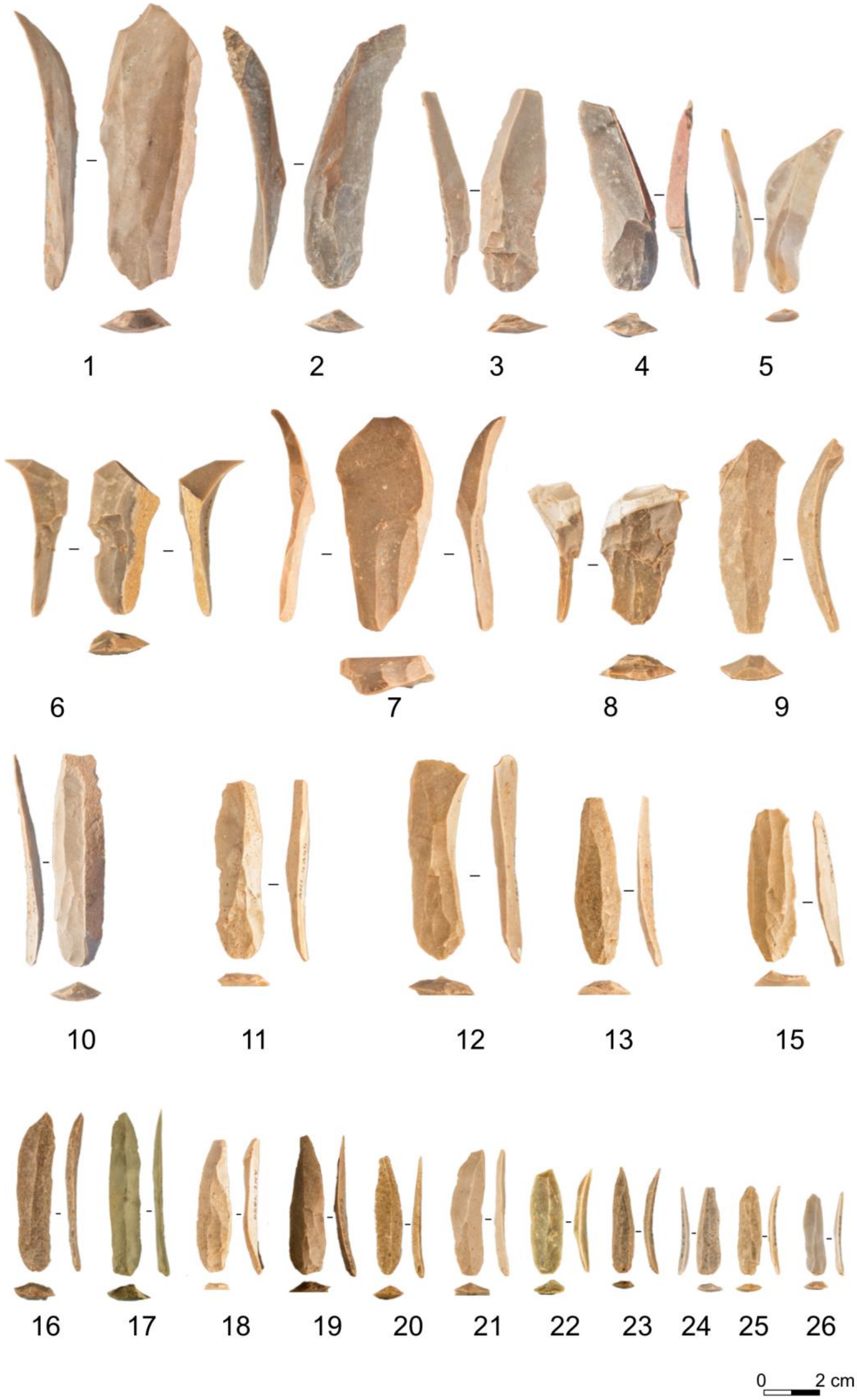

***Fig 2*. Sample of al-Ansab 1 AH1 blades and bladelets included in the analysis.** *1 – 5 asymmetrical blades, 6 – 9 overshot blades, 10 – 15 simple blades, 16 – 26 simple bladelets. Pictures Jacopo Gennai.*

Româneşti-Dumbrăviţa I GH3

The artefacts from 2016–2019 with single coordinates have been fully analysed by one of us (J.G.) to provide a technological and taxonomic assessment (Chu et al., 2022; Gennai et al., 2021). The analysis showed that a complete reduction process is present on-site, mostly using locally sourced raw materials. The production is focused on the obtention of bladelets from volumetric, unidirectional cores (Fig 3). Cores are either semicircumferential or narrow-faced. Despite the assemblage being blade-bladelet oriented, there is a significant amount of non-cortical flakes. The main interpretation is that the lower quality of the used raw material influenced the knappers' core preparation and that flakes might come from various core management activities, such as partial striking platform rejuvenation. Bladelets are mostly produced from the central flat part of the flaking surface and are generally encased by blade-sized negatives (Gennai et al., 2021). The assemblage has been attributed on techno-typological and dating grounds to the Protoaurignacian (Chu et al., 2022).

Fig 3. Sample of Româneşti-Dumbrăviţa I GH3 blades and bladelets included in the analysis*. 1 – 5 asymmetrical blades, 6 – 10 overshot blades, 11 – 16 simple blades, 17 – 25 simple bladelets. Pictures Jacopo Gennai.*

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Grotta di Fumane A2-A1

Fumane is one of the key sites in Mediterranean Europe for understanding the technological and behavioural variability of the Protoaurignacian. As such, its lithic assemblages have been analysed over the years by several scholars (Bertola et al., 2013; Broglio et al., 2005; De Stefani, 2003; Falcucci et al., 2020, 2017; Gennai et al., 2021). In addition to traditional technological approaches, the earliest Protoaurignacian assemblages have been studied using functional (Aleo et al., 2021), 3D geometric morphometrics, and reduction intensity approaches. Recently, Falcucci and colleagues (Falcucci et al., 2024a) assessed the integrity of the Aurignacian lithic assemblages using a break connection method (Bordes, 2002) to conjoin broken blades, further combining spatial analysis and lithic taphonomy. Their study showed that A2 and A1 should be considered a single analytical unit, characterised by palimpsest formation and marked spatial variability. Therefore, in this study, the two assemblages are merged and analysed together as A2-A1. Regarding the spatial sample, the lithics studied in this paper come from the cave exterior and the area around the drip line, where postdepositional processes are less pronounced compared to the cave interior (Falcucci et al., 2024a, 2020). At Fumane, complete reduction sequences were carried out on-site, with evidence of core initialisation, maintenance, and retooling activities. Bladelet production was mostly based on the use of platform unidirectional cores, with marginal percussion used to extract slender bladelets. In most cases, striking platforms are plain, and reduction procedures were aimed at isolating convergent flaking surfaces to extract pointed and relatively straight bladelets, which were frequently modified by marginal retouching (Fig 4). Carinated technology was used only marginally to produce short and curved bladelets. The dataset analysed in this study is a subset of the main Fumane dataset published on Zenodo (Falcucci et al., 2024b) and associated with the recent reanalysis of the Aurignacian deposit. The Zenodo dataset contains all Aurignacian and Gravettian lithics from the entire excavation area.

Fig 4. Sample of blades and bladelets from Fumane A2-A1 included in the analysis. *1, 5, 14 Semi-cortical blades, 2–4 Simple blades, 6 Neo-crested blade, 7, 16 Semi-cortical blades with bladelet removals, 8–10, 15 Lateral blades, 11–13, 19–23 Simple bladelets, 14 Naturally backed semi-cortical blade, 17–18 Small blades with bladelet scars, 24 – 28 Bladelets with lateral retouch. Photos: Armando Falcucci*

Les Cottés US04-inf

The site of Les Cottés features a stratigraphy spanning every known cultural technocomplexes from the Middle-to-Upper Palaeolithic transition in France: Mousterian, Châtelperronian, Protoaurignacian and Early Aurignacian (Roussel and Soressi, 2013). Between 2006 and 2018, excavations supervised by M. Soressi led to significant methodological advances in radiometric dating (Jacobs et al., 2015; Talamo et al., 2012), archaeozoology (Welker et al., 2015), lithic technology (Falcucci et al., 2018; Porter et al., 2019, 2016), palaeoenvironmental studies (Frouin et al., 2013) and palaeogenomics (Hajdinjak et al., 2018; Slon et al., 2017). The lithic assemblage analysed here (Fig 5) was retrieved from the lower part of the stratigraphic unit 04 (US 04 inférieure) attributed to the Protoaurignacian (Bataille et al., 2018; Bazile, 2002; Bon, 2002; Bon and Bodu, 2002; Falcucci et al., 2017; Porraz et al., 2010; Roussel and Soressi, 2013; Slimak et al., 2006; Tafelmaier, 2017; Teyssandier, 2023). The typological spectrum is largely dominated by retouched bladelets, followed by marginally retouched blades, which outnumber scrapers, burins and other tools. This proportion confirms the differentiation from Early Aurignacian contexts, such as US 04 supérieure (Falcucci et al., 2018; Le Brun-Ricalens, 2005; Roussel and Soressi, 2013; Teyssandier, 2023) . The débitage mainly aims at the production of bladelets, using primarily unidirectional reduction processes. Bladelets are produced either through a somewhat flexible frontal reduction modality on narrow surfaces of varied flint volumes, or through a more standardised convergent reduction modality on wide surfaces, requiring the removal of convergent elongated products from the sides of the flaking surface. This behaviour has recently been emphasized in many Protoaurignacian contexts (e.g. (Falcucci et al., 2017; Gennai et al., 2021)). The production of blades stems either from a semicircumferential modality, or sometimes from a frontal modality on narrow surfaces. While the narrow-face cores may produce blades and bladelets successively, this assemblage reveals a clear independence of both productions.

Fig 5. ***Sample of Les Cottés US 04inf blades and bladelets included in the analysis****. 1 – 4 overshot blades, 5 – 8 asymmetrical blades, 9 – 15 simple blades, 16 – 23 simple bladelets.s Pictures Leonardi Carmignani (4, 6, 9, 11, 13-17, 19-23) and Vincent Niochet (1-3, 5, 7-8, 10, 12, 18).*

Creation of the database

We focused on complete blanks and mesiodistal or mesioproximal fragments that preserve a significant portion of the original blank. This approach allows for the inclusion of attributes relevant to specific parts of the blank—for instance, platform attributes apply only to blanks with a preserved platform (i.e., the proximal part), while attributes such as distal end morphology are assessed only in artefacts retaining a distal portion. At the same time, it maintains qualitative rigour by excluding smaller fragments, such as isolated distal, mesial, and distal fragments, which may lead to erroneous observations due to their highly localised characteristics.

Reproducibility is a delicate matter in lithic studies, and it has a severe impact on the understanding of prehistoric human behaviours, as lithics are one of the most common sources of information for the Palaeolithic. Nonetheless, few studies delved into the inter-analysts' reproducibility and the problem of reproducibility impacts more qualitative analysis approaches than quantitative ones. The four assemblages analysed in this study were examined separately by analysts trained in the *chaîne opératoire* approach. They collected both qualitative and quantitative attributes, with the latter known for its higher reproducibility index (Pargeter et al., 2023). The data collection did not follow a controlled experiment, but they were collected using traditional standard attribute definitions (Andrefsky, 2005; Inizan et al., 1999; Scerri et al., 2016). Even though we used similar attributes and definitions, adjustments were needed.

We defined blades, bladelets and flakes according to standard criteria: a blade and a bladelet feature subparallel lateral edges and an elongation of 2 or greater, with a metrical threshold of 12 mm in width separating blades from bladelets (Andrefsky, 2005; Inizan et al., 1999; Tixier, 1963). A unimodal histogram of blade and bladelet width is typically interpreted as evidence of continuous knapping, with a gradual transition from blades to bladelets (Cascalheira, 2019). To assess the universality of this metrical threshold, we plotted the distribution of blade and bladelet widths using 1 mm bins. We ensured comparability by analysing similarly sized samples, excluding retouched blanks, and adjusting the sample size to match the smallest assemblage (510 blanks from Româneşti-Dumbrăviţa I GH3). For the assemblages from Al-Ansab 1 AH1, Grotta di Fumane A2-A1, and Les

Cottés 04-inf, sampling was conducted while maintaining the original proportions of blades and bladelets. The width values of the sampled artefacts were grouped into 1 mm intervals, and our analysis compared the median and mode widths of these samples against a threshold of 12 mm, which is commonly used to differentiate between blades and bladelets.

Al-Ansab 1 AH1

The Al-Ansab 1 AH1 (AN) database consists of 2050 entries, corresponding to 948 blades, 809 bladelets and 293 flakes (Table 1). The technological analysis study sample consists of single plotted complete and semi-complete blanks and cores recovered during the 2009–2011 and 2018 campaigns. The sample is a casual one encompassing areas with the highest concentrations of artefacts. Flakes tend to be complete, while blades and bladelets are fragmentary at least by half.

The AN assemblage consists of mainly high-quality and local tabular cherts found in nearby outcrops (<1 km) (Parow-Souchon et al., 2021). The whole lithic reduction is found on-site and no difference is noted between the different raw materials (Gennai et al., 2021; Parow-Souchon et al., 2021).

Table 1. Composition of AN database

	Complete		Mesiodistal		Mesioproximal		Total N	Total %
	N	%	N	%	N	%		
Blade	531	56,01%	238	25,11%	179	18,88%	948	100,00%
Bladelet	311	38,44%	195	24,10%	303	37,45%	809	100,00%
Flake	269	91,81%	11	3,75%	13	4,44%	293	100,00%
	1111	54,20%	444	21,66%	495	24,15%	2050	100,00%

Româneşti-Dumbrăviţa I GH3

The Româneşti-Dumbrăviţa I GH3 (ROM) database consists of 1094 entries, corresponding to 262 blades, 288 bladelets and 544 flakes (Table 2). The sample consists of the whole piece-plotted complete and semi-complete artefacts excavated in 2016 – 2019, excluding square P104. Flakes tend to be complete, while blades and bladelets are fragmentary at least by half.

The ROM assemblage shows mostly local (<10 km) procurement (Ciornei et al., 2020). Blocs were found in primary, sub-primary locations or river gravels and imported on-site as minimally modified cores (Ciornei et al., 2020). Longer-distance raw materials (13 – 60 km) were imported as prepared cores too (Ciornei et al., 2020). A single artefact is made of Carpathic obsidian and imported as a finished tool (Chu et al., 2022; Ciornei et al., 2020). Therefore, most of the reduction process happened on-site and no difference in the lithic reduction process is noticed between the different raw materials (Chu et al., 2022). The local raw material is often described as of lower knapping quality, featuring internal cracks and a coarser texture, nevertheless, it did not impede the technological goals and the development of a frankly Aurignacian assemblage (Chu et al., 2022).

Table 2. Composition of ROM database

	Complete		Mesiodistal		Mesioproximal		Total N	Total %
	N	%	N	%	N	%		
Blade	131	50,00%	48	18,32%	83	31,68%	262	100,00%
Bladelet	106	36,81%	95	32,99%	87	30,21%	288	100,00%
Flake	481	88,42%	18	3,31%	45	8,27%	544	100,00%
	718	65,63%	161	14,72%	215	19,65%	1094	100,00%

Grotta di Fumane A2-A1

The Grotta di Fumane A2-A1 (FUM) database consists of 4647 entries, corresponding to 1065 blades, 2996 bladelets, 581 flakes, and 5 undetermined (Table 3). Finds bigger than 15 mm were coordinated during excavation, the analysis focused on these artefacts. A third of the blades and flakes are complete, while only around 15% of the bladelets are complete. 40% of the bladelets are mesial fragments. FUM is characterised by abundant retouched blanks, especially bladelets, which may have skewed fragment representation. The dataset is a subset of the main Fumane dataset, which is available under a CC BY 4.0 license on Zenodo (Falcucci et al., 2024b).

The FUM assemblage consists mostly of high-quality flint embedded in the carbonate formations of the western Monti Lessini, ranging from the Upper Jurassic to the Middle Eocene. They are available within 5-15 km from the site. The most common, determined with macroscopic features, are cherts embedded in the Maiolica, the Scaglia Rossa, the Scaglia variegata, and the Ooliti di San Virgilio formations (Falcucci et al., 2017). Flint also abounds in loose coarse streams or fluvial gravels, slope-waste deposits, and soils in the immediate surroundings of the cave (Bertola, 2001). Jurassic and Tertiary calcarenites, frequently found in large-sized and homogeneous nodules, were almost exclusively used to produce blades (Bertola et al., 2013).

Table 3. Composition of FUM database*. The list excludes three angular debris listed in the dataset by (Falcucci et al., 2024b), as they cannot be associated with any specific blank class.*

	Almost complete		Complete		Proximal		Mesioproximal		Mesial		Mesiodistal		Distal		Undetermined		Total N	Total %
	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%		
Blade	19	1,80 %	287	27,13 %	71	6,62%	303	28,17 %	251	23,72 %	119	11,15 %	15	1,42 %		0,00%	1065	100,00 %
Bladelet	15	0,47 %	472	15,79 %	89	3,01%	862	28,81 %	1170	39,06 %	352	11,73 %	36	1,12 %		0,00%	2996	100,00 %
Flake	9	1,56 %	214	36,85 %	81	14,01 %	210	36,16 %	19	3,11%	36	6,23%	6	1,04 %	6	1,04%	581	100,00 %
Undetermined		0,00 %		0,00%		0,00%		0,00%	2	40,00 %		0,00%		0,00 %	3	60,00 %	5	100,00 %

	43	0,91%	974	21,04%	241	5,22%	1375	29,54%	1442	30,99%	507	10,89%	57	1,17%	11	0,24%	4647	100,00%

Les Cottés US04-inf

The Les Cottés US04-inf (CTS04inf) database consists of 839 entries, corresponding to 476 blades, 353 bladelets and 10 flakes (Table 4). Finds bigger than 15 mm were coordinated during excavation. A few pieces were retrieved in the sieves and allocated an individual identification. About 20% of blades and bladelets and a third of flakes are complete. More than half of each category are mesioproximal fragments. Around one-quarter of blades and bladelets are mesiodistal fragments. Artefacts come mainly from the northern and eastern areas of the recently excavated surface, where each stratigraphic unit is well-separated by low-density layers and post-depositional processes are minimal.

The artefacts are made of three sub-types of Upper Turonian flint, available in the immediate surroundings of the cave under the shape of slabs and nodules (Primault, 2003). Our original assemblage selected for this study consisted of 1303 complete and sub-complete blades, bladelets and informative flakes, sampled in stratigraphically safe areas. Almost two-thirds of the pieces were made on local raw materials 64,5%. However, only local materials are used in the three other sites of this study. We consequently chose to remove a part of the sample comprising the raw materials coming from more than 20 km of the site (21% of the initial selection) and the ones which remained undetermined (15%). This led to reduce the potential technological and statistical biases that would have stemmed from different economic patterns between sites.

Table 4*. *Composition of CTS04inf database *after selecting only local raw materials*

	Complete	Mesioproximal	Mesiodistal	Total N	Total %

	N	%	N	%	N	%		
Blade	103	21,64%	249	52,31%	124	26,05%	476	100,00%
Bladelet	74	20,96%	195	55,24%	84	23,80%	353	100,00%
Flake	3	30%	6	60,00%	1	10,00%	10	100,00%
	180	21,45%	450	53,64%	209	24,91%	839	100,00%

Merging the sites' databases into one

The database was produced using a similar analytical approach and employed interoperable terms. Nevertheless, some observations required homogenisation—at the very least in terms of formatting, capitalisation, and terminology—to ensure proper processing in R (R Core Team, 2023). The software R was chosen to handle all processes of data wrangling and analysis to foster reproducibility due to its open-source nature and widespread adoption in data analysis (R Core Team, 2023). The homogenisation processes, resulted in a merged database containing 37 attributes, most of which were already present in the original databases and have been renamed, while others were derived from existing data (Table 5) using the functions available in the R Tidyverse environment (Wickham et al., 2019). The code used for data manipulation and attribute homogenisation and analysis is provided as SI file and available on Github alongside all datasets: https://github.com/ArmandoFalcucci/EUP_Comparison.

Changes included:

- Preservation**:** almost complete blanks from Fumane have been registered as complete ones.
- Cortex: originally the AN, ROM, and CTS04inf databases showed cortex presence in 25% steps. The FUM database in 33% steps. After carefully reviewing occurrences in blanks and their technological role we decided to rename them as semicortical blanks with up to 50% (AN, ROM, CTS04inf) and up to 66% (FUM) cortical surface. Blanks above these thresholds are renamed Extensively cortical. Blanks having 0% cortex have been renamed to No cortex, those with 100% cortex are fully cortical.

- Cortex position: the position of the cortex on the blanks' dorsal faces featured too many observations, some being single observations. This would have hindered the comparability. Therefore, the cortex position observations have been changed accordingly to distal, distal and lateral, distal and proximal, dorsal, dorsal and distal, dorsal and lateral, lateral, proximal, proximal and lateral, and undetermined. Blanks without cortex presence have been left blank.
- Platform**:** platform types have been reduced to cortical, plain, linear, punctiform, facetted, and undetermined. Blanks without a proximal part, i.e. mesiodistal ones, have been left blank. Concave (AN, ROM, CTS04inf) and double (FUM) platforms have joined plain ones. Dihedral platforms have joined facetted ones. Natural platforms have been named cortical. Crushed platforms in the AN and ROM databases joined the undetermined ones, while in CTS04inf they joined the linear ones after the observer noticed they mostly related to this category. Abraded platforms (FUM) joined the undetermined ones.
- Outline morphology: the dorsal shape view's observations have been reduced to convergent, parallel, off-axis. Only CTS04inf kept the "other" observation. This attribute has been left blank in case of flake, tablet or mesioproximal blank.
- Cross section: the shape of the transversal cross-section has been reduced to polyhedric or triangular. Polyhedric has been preferred to trapezoidal. This attribute has been left blank in case of flake or tablet blanks.
- Profile: the artefact longitudinal profile observations have been reduced to straight, slightly curved, curved, and twisted. Twisted was not present in FUM, as it is expressed by a separate attribute: Torsion. Therefore, AN and ROM blanks with a calculated curvature value and a twisted profile could be changed into straight, slightly curved, or curved. Those that did not have a calculated value or CTS04inf blanks kept the twisted observation. Whether a longitudinal profile is twisted or not is expressed by the new attribute
- Torsion: This attribute has been left blank in case of flake or tablet blank.
- Distal end morphology**:** the artefact's termination longitudinal profile has been reduced either to feathered or plunging. Hinged terminations have been joined to the undetermined, and the

stepped terminations have been left blank: both these observations did not give any technological information.

- Dorsal scar 1: was derived and rationalised from dorsal scar 2. Observations were reduced to unidirectional, bidirectional, centripetal, crossed, orthogonal, other, and undetermined. In case another direction was joining the unidirectional or bidirectional variant, but they were not prevalent, the observation unidirectional/bidirectional+other direction was used.

Table 5. Attributes and their homogenisation process. *Equivalent attributes in the databases of each author, new attribute names in the merged database, and the meaning of the attribute*

Gennai Attribute Name	Niochet Attribute Name	Falcucci Attribute Names	New Names	Explanation
Site	Site	Site	Site	assemblage site
			Technocomplex	Technocomplex
Layer	Layer	Layer	Layer	stratigraphical unit
Piece Original ID	Piece Original ID	ID	ID	ID of the single artefact
Entirety	Entirety	Preservation	Preservation	whether the artefact is complete or fragmentary. If fragmentary Proximal, Mesio-Proximal, Mesial, Mesio-Distal, Distal
		Cortex.y.n	Cortex.y.n	if there is cortex or not
CxSimpl	CxSimpl	Cortex	Cortex	Cortical surface extent

CxPosition	CxPosition	Cortex.position	Cortex.position	position of the cortical surface on the artefact
Length	Length	Length	Length	artefact length on its technological axis
Width	Width	Width	Width	artefact width at artefact mid-length perpendicular to the technological axis
Thick	Thick	Thickness	Thickness	artefact thickness at artefact mid-length perpendicular to the width
El	El	Elongation	Elongation	artefact length/artefact width
		robustness	Robustness	Artefact width/artefact thickness
ButtType	ButtType	platform.type	Platform	type of platform
BulbMorph	BulbMorph	bulb.type	Bulb	type of Bulb
Lipp	Lipp	Lip	Lip	presence of a lip, recorded on laminar artefacts
OvAb	OvAb	dorsal.thinning	Abrasion	presence of overhang abrasion

				on the proximal dorsal surface
Axiality	Axiality	axiality	Axiality	if the artefact technological axisi correspond or not to its morphological axis
Out	Out	blank.shape	Outline.morphology	dorsal view of the artefact
Symmetry	Symmetry	cross.section.symmetry	Symmetry	whether the artefact cross section is symmetric or not at mid-length
CrossSectMorph	CrossSectMorph	cross.section	Cross.section	artefact cross section shape at mid-length
Pro	Pro	curvature	Profile	artefact longitudinal profile
		Torsion	Torsion	whether the artefact's longitudinal profile is twisted or not
DEndMorph	DEndMorph	distal.end.profile	Distal.end.morpho	artefact's termination longitudinal profile
			Blank.type1	Flake or Laminar

StructureCat	StructureCat	blank	Blank.type2	Flake, Blade, Bladelet
TechCat	TechCat	technology	Technology.Phase	phase of the reduction
Cat	Cat	technology.ext	Technology.Ext	technological category
NegN	NegN	scar.count	Number.negatives	number of negatives on the dorsal surface
NegType	NegType	bladelet.neg.blade & blade.neg.flake	Negatives.type	
			Dorsal.scar.1	Negatives orientation along the technological axis, simplified
NegO	NegO	scar.pattern	Dorsal.scar.2	Negatives orientation along the technological axis
R	R	Class	Tool	whether the artefact is retouched or not
Rpos	Rpos	retouch.position	Retouch.Position	Retouch position on the artefact's faces
Rloc	Rloc	RLoc	Retouch Location	retouch localisation on the artefact
Rdis	Rdis	RDist	Retouch Distribution	retouch extent on the artefact

Typology	Typology	typology	Typology	Synthetic tool type determination

The result is a database comprising 6698 entries across the four assemblages. AN accounts for 2050 entries, ROM for 1094 entries, FUM for 2715 entries, and CTS04inf for 839 entries (Table 6).

Table 6. Final merged database composition

	Complete		Mesiodistal		Mesioproximal		N total	% total
	N	%	N	%	N	%		
AN	**1111**	**36,75%**	**444**	**38,79%**	**495**	**19,53%**	**2050**	**30,58%**
Blade	531	17,59%	238	20,84%	179	7,06%	948	14,16%
Bladelet	311	10,24%	195	16,99%	303	11,95%	809	12,04%
Flake	269	8,91%	11	0,96%	13	0,51%	293	4,38%
CTS04inf	**180**	**5,96%**	**209**	**18,30%**	**450**	**17,75%**	**839**	**12,53%**
Blade	103	3,41%	124	10,86%	249	9,82%	476	7,11%
Bladelet	74	2,45%	84	7,36%	195	7,69%	353	5,27%
Flake	3	0,10%	1	0,09%	6	0,24%	10	0,15%
FUM	**1011**	**33,50%**	**329**	**28,81%**	**1375**	**54,24%**	**2715**	**40,55%**
Blade	306	10,14%	119	10,42%	303	11,95%	728	10,87%
Bladelet	487	16,14%	174	15,24%	862	34,00%	1523	22,75%
Flake	218	7,22%	36	3,15%	210	8,28%	464	6,93%
ROM	**718**	**23,79%**	**161**	**14,10%**	**215**	**8,48%**	**1094**	**16,34%**
Blade	131	4,34%	48	4,20%	83	3,27%	262	3,91%
Bladelet	106	3,51%	95	8,32%	87	3,43%	288	4,30%
Flake	481	15,94%	18	1,58%	45	1,78%	544	8,13%
Total	**3020**	**100,00%**	**1143**	**100,00%**	**2535**	**100,00%**	**6698**	**100,00%**

Variance analysis

We conduct a detailed variance analysis of attributes observed on different types of blanks—flake, blade, and bladelet. Initially, we explore the frequencies of these attributes within each blank class, comparing them between sites using the R packages ggstatsplot (Patil, 2021) and ggplot2 (Wickham, 2016) for calculation and visualisation.

We then analysed sets of attributes by grouping them into technologically meaningful (Tostevin, 2012) domains. A similar approach is described in (Cascalheira, 2019). We adapted to our needs two of the domains defined by (Tostevin, 2012) and grouped the variables into three domains:

- **Platform domain**: This domain includes the Platform and Abrasion attributes and examines their relationship with the Robustness index. We hypothesise that less-prepared platforms are associated with the absence of abrasion and blanks with low robustness index—i.e., those with a smaller ratio between width and thickness, indicating they are narrower. Also, we hypothesise that given the shape, blanks with a high robustness index would result in wider platform types like linear or plain. The Platform domain groups the Platform and Abrasion attributes and tests them against Robustness. Blanks with undetermined values, those that do not preserve the proximal part, cortical platforms, and flakes are excluded. The Solutrean dataset lacks the Abrasion attribute.
- **Convexity Domain**: This domain encompasses attributes such as Axiality, Outline, Symmetry, Cross-section shape, Torsion, Profile, and Distal end longitudinal profile. These attributes help define the products of the reduction process and infer their role and position within the core reduction. We assume that skewed, bent, and irregular shapes indicate management products—typically involving the removal of lateral and distal core ends to create convexities—while on-axis, straight, and regular shapes correspond to target products, which do not primarily aim to produce convexities. The Convexity domain groups the attributes of Axiality, Outline, Symmetry, Cross-section shape, Torsion, Profile, and Distal end longitudinal profile. Blanks with undetermined or missing values, as well as flakes, are excluded from the analysis. The Solutrean

dataset lacks an attribute reporting cross-section symmetry, and observations like "Divergent" and "Biconvex" outlines, not being recorded in the other assemblages, were removed.

- **Retouch Domain**: This domain groups the attributes of Retouch position, location, and distribution.

To visualise and analyse the associations within these domains, we used Multiple Correspondence Analysis (MCA - (Abdi and Valentin, 2007). MCA was performed using the FactoMineR package (Lê et al., 2008), and the results were plotted along two most significant orthogonal axes of variation. Attribute observations are then positioned within a two-dimensional space, forming clusters that are colour-coded based on their contribution to explaining variance.

We began the analysis by organising categorical variables into a Burt table—a contingency table that displays the frequency of each category and their co-occurrences. The diagonal blocks of the Burt table show single variable frequencies (e.g., the number of Plain platforms), while the off-diagonal blocks show co-occurrences (e.g., the number of Plain platforms with Abrasion). We apply Singular Value Decomposition (SVD) to the Burt table to extract principal components, representing directions in which the data varies the most. The analysis focuses on a bidimensional representation by selecting the first two principal components. To enhance interpretation, we used supplementary variables (also called passive or illustrative variables) in the MCA plot. These supplementary variables, while not included in the initial principal components calculations, are projected into the same factor space to provide context for the clusters without altering the structure defined by the active variables. Supplementary variables in this analysis include blank type – blade and bladelet -, the name of the assemblages studied, and the technocomplexes to which they are attributed. The labels for the supplementary variables in the plots are as follow:

AN.bladlt = Al-Ansab AH1 bladelets

AN.Blade = Al-Ansab AH1 blades

ROM.bladlt = Româneşţi-Dumbrăviţa I GH3 bladelets

ROM.Blade = Româneşţi-Dumbrăviţa I GH3 blades

FUM.bladlt = Grotta di Fumane A1-A2 bladelets

FUM.Blade = Grotta di Fumane A1-A2 blades

CTS04inf.bladlt = Les Cottés 04inf bladelets

CTS04inf.Blade = Les Cottés 04inf blades

The supplementary categories representing technocomplexes are:

Solu = Solutrean

Proto = Protoaurignacian

S.Ahm = Southern Ahmarian

To further understand the clusters formed by the attributes and supplementary categories, we computed distance matrices using the ‘factoextra’ package (Kassambara and Mundt, 2020). These matrices are visualised through heatmaps, where colours range from red (indicating strong association or no distance) to blue (indicating weak association or maximum distance). This visualisation helps identify closely related attributes, though it does not define precise mid-distance score cutoffs. The distance matrices were calculated using the Euclidean distance between the active variables and the supplementary categories on the biplot (first two dimensions), assessing similarity based on the coordinates derived from the MCA. We used the `get_dist` function from the ‘factoextra’ package for this calculation.

To refine our understanding of the lithic reduction attributes in our dataset, we incorporated a control group consisting of blanks attributed to the Solutrean period dated to the Last Glacial Maximum and excavated in Spain and Portugal. This dataset compiled by Cascalheira (Cascalheira, 2019) is one of the few freely available and reusable datasets, and, most importantly, it is comparable with our EUP assemblages. The Solutrean technology relies on volumetric reduction for producing blades and bladelets, like the EUP, but is chronologically distinct enough – circa 20,000 years - to exhibit its unique lithic reduction signature. Including the Solutrean control group serves multiple purposes. First, it provides a comparative benchmark against which the patterns in our EUP dataset can be assessed. Despite the technological similarities, the Solutrean data's distinct chronological position may reveal unique characteristics and variations in lithic reduction practices. This comparison helps validate the clusters and patterns identified in our analysis, strengthening the reliability of our findings. Cascalheira's dataset, derived from extensive technological analyses of Iberian Solutrean assemblages, offers a detailed and open-access record of lithic attributes. This dataset is particularly valuable because it includes artifact-level entries rather than just frequency or presence/absence data, which is rare in open-access technological datasets. We performed attribute homogenisation to ensure meaningful integration of this control group with our dataset. This process aligned the attributes from both datasets to minimise biases and ensure comparability, allowing us to incorporate the Solutrean data effectively into our analysis.

Results

Exploratory plots

We compare frequencies of attributes' observations across blanks, assemblages, and technocomplexes (see the Supporting Information). The results highlight similarities between the different assemblages. Most blanks are non-cortical, particularly bladelets. Laminar blanks most commonly exhibit lateral and distal cortical positions, while flakes tend to have a higher proportion of dorsal cortex. Platforms are predominantly non-facetted (plain, linear, or punctiform). Abrasion of the proximal part is frequently observed in both blades and bladelets. Blades and bladelets typically have a regular, on-axis shape, with bladelets tending to be more convergent in silhouette and triangular in cross-section. A straight or slightly curved profile is the norm for laminar artefacts, whereas curved profiles are more common in blades. Plunging distal ends are more frequently seen in blades, though they are not predominant. Twisted artefacts are rare. Unidirectional knapping direction is overwhelmingly present in both blades and bladelets. Retouch positions show distinct patterns across sites: while blades are predominantly retouched on their dorsal face, bladelets exhibit a progressive increase in retouch on the ventral face as one moves westward (from AN to CTS04inf).

Metrical data of blades and bladelets from the four tested assemblages

We present here the histograms of widths for each assemblage. We use width values, as length measurements are more influenced by the shape and dimensions of the flaking surface. The histograms and density distributions for each assemblage show that the median width of the blanks is close to the 12 mm threshold. Notably, the peaks of the histograms occur around or below this threshold. Specifically, the mode, which represents the bin with the highest density of observations, consistently falls below the 12 mm threshold across all assemblages. For instance, the mode values are 9 mm for AN, 9 mm for ROM, 10.5 mm for FUM, and 10.5 mm for CTS04inf. Furthermore, the median widths of the combined samples are 12.3 mm for AN, 11.8 mm for ROM, 10.9 mm for FUM, and 13.3 mm for CTS04inf. This suggests that while there is a range of blade and bladelet types within the samples, bladelets are particularly well-represented, especially in the FUM assemblage (Fig. 6). We tested the same excluding mesiodistal fragments, while the mode values remain similar in the four assemblages, the combined blades and bladelets median value increase in AN and ROM towards 12.5 mm (SIFig 40). We also compared the width values of Protoaurignacian, Southern

Ahmarian and Solutrean assemblages, without finding meaningful variations between them (SIFig 41).

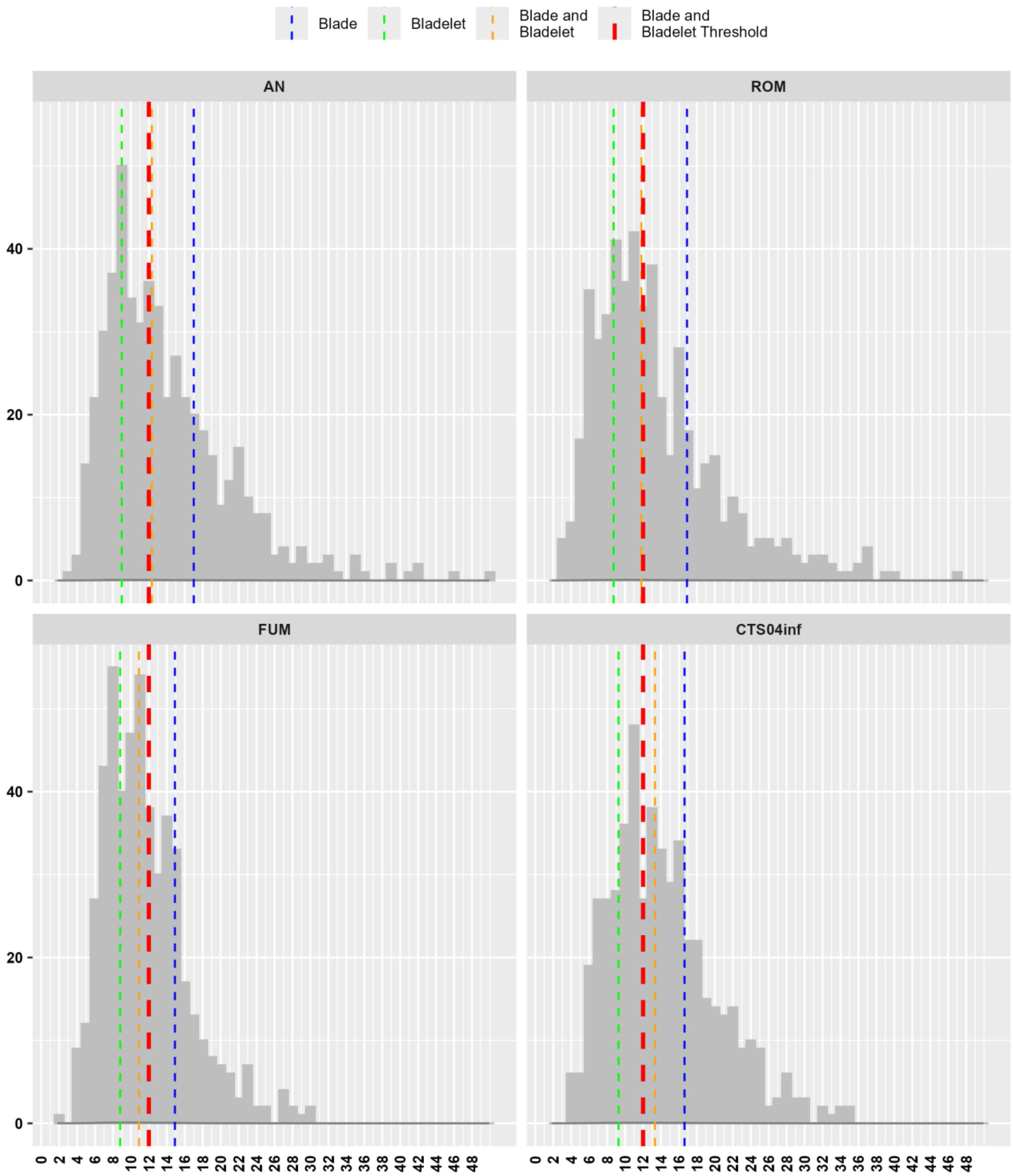

***Fig 6. Histogram of available width for each assemblage, values are binned by 1 mm**. Blades and bladelets together. dashed lines represent median values (blue=blades, green=bladelets, orange=all blanks) and the arbitrary 12 mm threshold between blades and bladelets (red)*

Multiple Correspondence Analysis

Platform domain

The Platform domain, with the Solutrean assemblages alongside Early Upper Paleolithic (EUP) assemblages, consists of 6183 blade and bladelet entry artefacts. The first two dimensions of the correspondence analysis explain 38.8% of the total variance, with Dimension 1 accounting for 21.0% and Dimension 2 for 17.8% (Fig 7). Dimension 1 highlights a contrast between Cortical platforms and High robustness (blanks that are thinner or wider). Low robustness is primarily associated with Cortical platforms and the Solutrean technocomplex, as confirmed by their closer Euclidean distances. Conversely, Linear platforms are linked with High robustness, reflecting their shorter Euclidean distance to this attribute. The Protoaurignacian and Southern Ahmarian technocomplexes cluster closer to punctiform platforms and are strongly associated with slender blanks. In contrast, the Solutrean technocomplex is predominantly linked to thicker blanks relative to their width. Overall, the Protoaurignacian and Southern Ahmarian assemblages, cluster on the left side of Dimension 1, further illustrating their association with Punctiform platforms and slender blanks, in contrast to the Solutrean's association with Cortical platforms and thicker blanks.

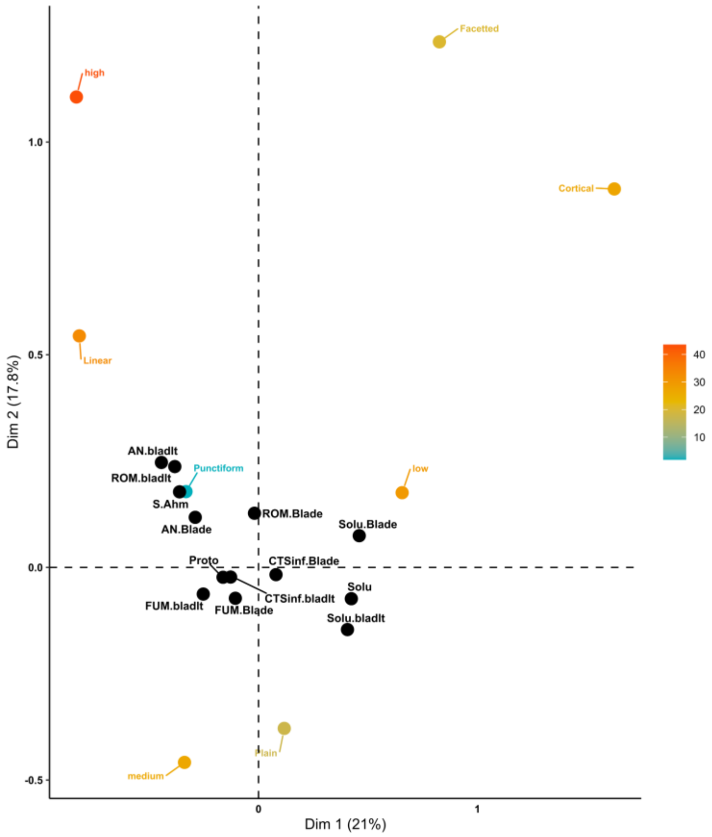

Fig 7. Platform domain MCA biplot of EUP and Solutrean assemblages. *The active variables are coloured from light blue to dark orange according to their total contribution to the two dimensions. The supplementary qualitative categories are coloured in black.*

Focusing on the EUP assemblages, 3929 blade and bladelet artifacts were included in the Platform domain analysis. The first two dimensions of the correspondence analysis explain 40.0% of the total variance, with Dimension 1 accounting for 25.1% and Dimension 2 for 14.9% (Fig. 8). Dimension 1 is primarily defined by the contrast between the presence and absence of abrasion, with the absence of abrasion strongly associated with cortical platforms. In contrast, the presence of abrasion is closely linked to FUM blades and bladelets, as well as CTS04inf bladelets. Dimension 2 highlights the opposition between linear and plain platforms. High Robustness is strongly associated with linear platforms, while medium Robustness (9.07–17.8) is more closely linked to plain platforms. Based on their positions in the biplots and their Euclidean distances, CTS04inf blades show a stronger association with plain platforms, while AN and ROM bladelets are more closely related to Linear platforms. Overall, all sites cluster closely along Dimension 1, reflecting shared characteristics, but are distributed along Dimension 2 in a pattern corresponding to their geographic distances.

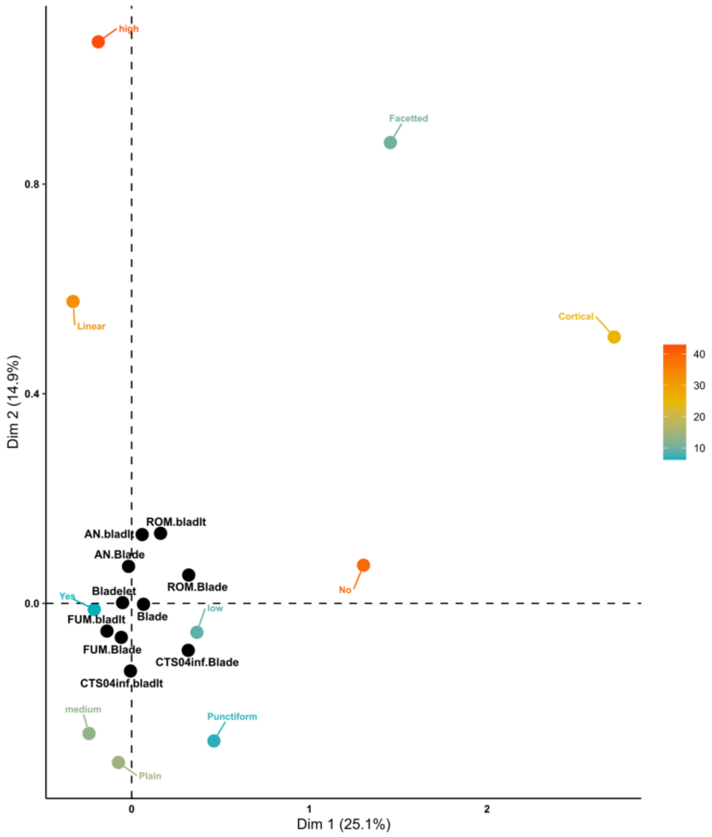

Fig 8. Platform domain MCA biplot of EUP assemblages. *The active variables are coloured from light blue to dark orange according to their total contribution to the two dimensions. The supplementary qualitative categories are coloured in black.*

Convexity domain

A total of 3834 blades and bladelets were included in the comparison between the Solutrean assemblages and the EUP assemblages for the convexity domain. The first two dimensions explain 62.1% of the total variance, with Dimension 1 accounting for 45.2% and Dimension 2 for 16.9% (Fig 9). Dimension 1 highlights the contrast between off-axis and on-axis morphologies. Off-axis attributes, along with the presence of torsion and plunging distal terminations, form one cluster, as indicated by their Euclidean distances. In contrast, axial morphologies cluster at the opposite end, characterized by the absence of torsion, symmetric cross-section shapes, and convergent outlines. The Protoaurignacian and Southern Ahmarian technocomplexes trend toward the off-axis cluster, although their distances place them closer to polyhedric cross-sections. The Solutrean technocomplex clusters at the opposite pole, with AN blades associated with plunging and slightly curved profiles, while ROM bladelets, AN bladelets, and CTS04inf blades form another distinct cluster. FUM blades and ROM blades are associated with polyhedric shapes and curved profiles, while FUM bladelets mostly cluster with the absence of torsion and regular morphologies, distinct from Solutrean blades and bladelets, which cluster around convergent and feathered profiles. Dimension 2 is characterized by twisted profiles, plunging distal end morphology, the presence of torsion, and curved profiles. Active variables associated with Dimension 2 include twisted and curved profiles, as well as feathered and plunging distal end morphologies. The supplementary categories most strongly associated with Dimension 2 are AN blades, CTS04inf bladelets, and FUM blades. Dimension 2 reveals an opposition between two clusters: one formed by twisted profiles and the presence of torsion, and the other by curved profiles and plunging distal terminations. No technocomplex correlates clearly with these clusters, although the Southern Ahmarian is closest to the curved profile cluster. Overall, the Solutrean dataset clusters internally with regular morphologies, the Protoaurignacian positions centrally, and the Southern Ahmarian trends toward the opposite end of the Solutrean. The Protoaurignacian and Southern Ahmarian are more closely related to each other than either is to the Solutrean.

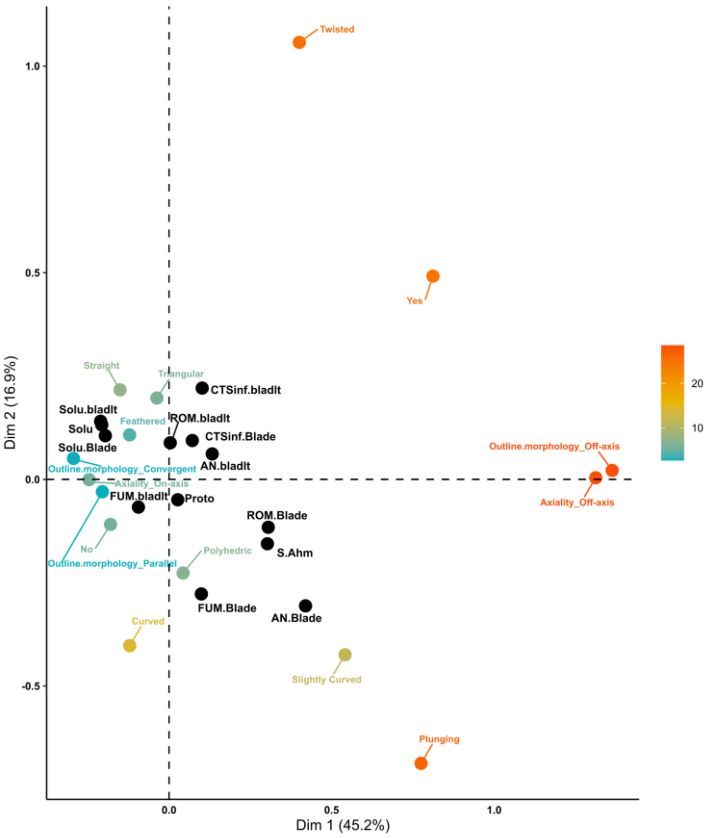

***Fig 9**. **Convexity domain MCA biplot of EUP and Solutrean assemblages.** The active variables are coloured from light blue to dark orange according to their total contribution to the two dimensions. The supplementary qualitative categories are coloured in black.*

Focusing on the EUP assemblages, 2192 blades and bladelets were included in the analysis. The first two dimensions account for 62.7% of the total variance, with Dimension 1 explaining 45.4% and Dimension 2 contributing 17.3% (Fig 10). Dimension 1 emphasizes the contrast between off-axis and on-axis morphologies. Off-axis attributes, along with the presence of torsion, form a distinct cluster, as indicated by their Euclidean distances. At the opposite end, axial morphologies are associated with the absence of torsion, symmetric cross-section shapes, and convergent outlines. The blade category and AN blades are closest to the off-axis cluster but are positioned nearer to slightly curved profiles and asymmetric cross-sections. FUM bladelets and the bladelet category align more closely with the on-axis group. Overall, the assemblages show some grouping but remain diverse in morphology. Dimension 2 contrasts variables within the same attribute group. Straight versus curved profiles, feathered versus plunging distal ends, and triangular versus polyhedric cross-section shapes are positioned at opposite ends of Dimension 2. Bladelets primarily cluster in the lower left quadrant, associated with feathered terminations, triangular cross-sections, and straight profiles, while blades tend to group in the upper quadrant. ROM and AN blades are characterized by off-axis terminations and asymmetric cross-sections, while FUM and CTS04inf blades display more regular morphologies with curved profiles. The biplot reveals a clear trend: blades from all assemblages predominantly cluster in the upper part of the plot, while bladelets are concentrated in the lower part. This pattern underscores the consistent characteristics within assemblages and highlights the distinct differences between blades and bladelets. It emphasizes the importance of studying them separately. Among the bladelets, FUM bladelets show the highest degree of morphological regularity.

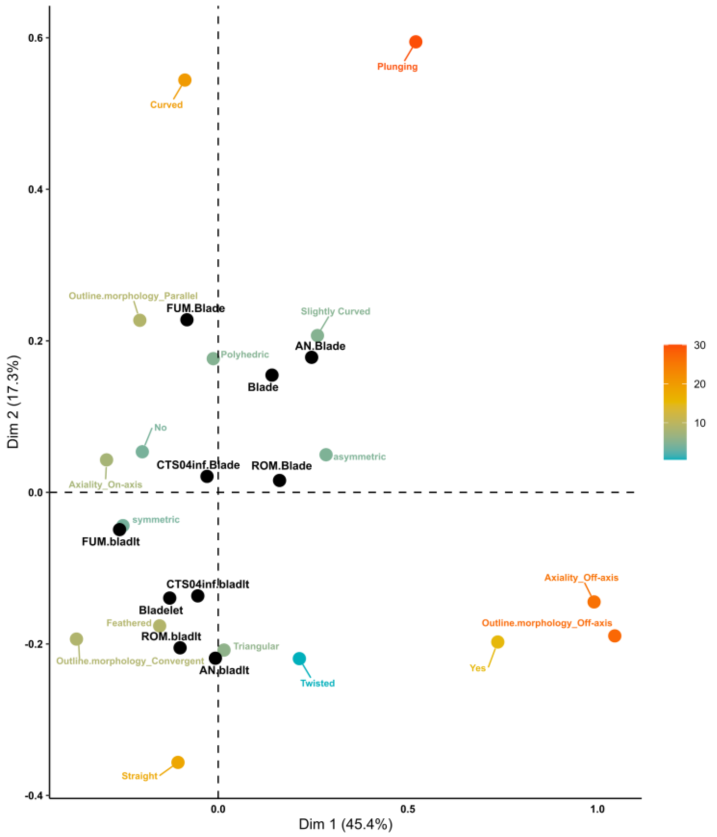

***Fig 10**. **Convexity domain MCA biplot of EUP assemblages.** The active variables are coloured from light blue to dark orange according to their total contribution to the two dimensions. The supplementary qualitative categories are coloured in black.*

Retouch domain

Only blades and bladelets with lateral retouch (n=572) were analysed, as they represent the most typical tool types of the EUP. The first two dimensions of the MCA explain 34.4% of the total variance, with Dimension 1 accounting for 25.2% and Dimension 2 for 9.2% (Fig 11). Dimension 1 highlights a contrast between continuous and partial retouch distribution. Retouch positions are largely independent of one another, with inverse retouch being closer to alternate than to direct, as expected. FUM bladelets are associated with alternate, bilateral, and continuous retouch, characteristic of classic Dufour bladelets, while CTS04inf blades, along with ROM and AN bladelets, cluster primarily with partial retouch. Dimension 2 reflects the opposition between direct and inverse retouch Positions. CTS04inf bladelets cluster strongly with the inverse position, while blades, particularly those from ROM and FUM, cluster with the direct position. Additionally, FUM, ROM, and AN's blades tend to cluster with left retouch Locations. Overall, AN and ROM assemblages cluster for both bladelets and blades, while all four sites cluster for blade retouch. This suggests a superregional unity in blade retouch practices. However, bladelet retouch becomes increasingly idiosyncratic moving westward. FUM bladelets as well as CTS04inf bladelets do not form a cluster but instead appear isolated, suggesting a specific retouching style distinct from each of these assemblages when it comes to bladelets. This geographical variability in bladelet retouch has been described in previous studies (Falcucci et al., 2018). The contrast between the unity in blade retouch and the variability in bladelet retouch highlights an intriguing pattern: eastern assemblages, such as AN and ROM, are much more similar to each other despite being attributed to different technocomplexes than to any of the other assemblages studied here.

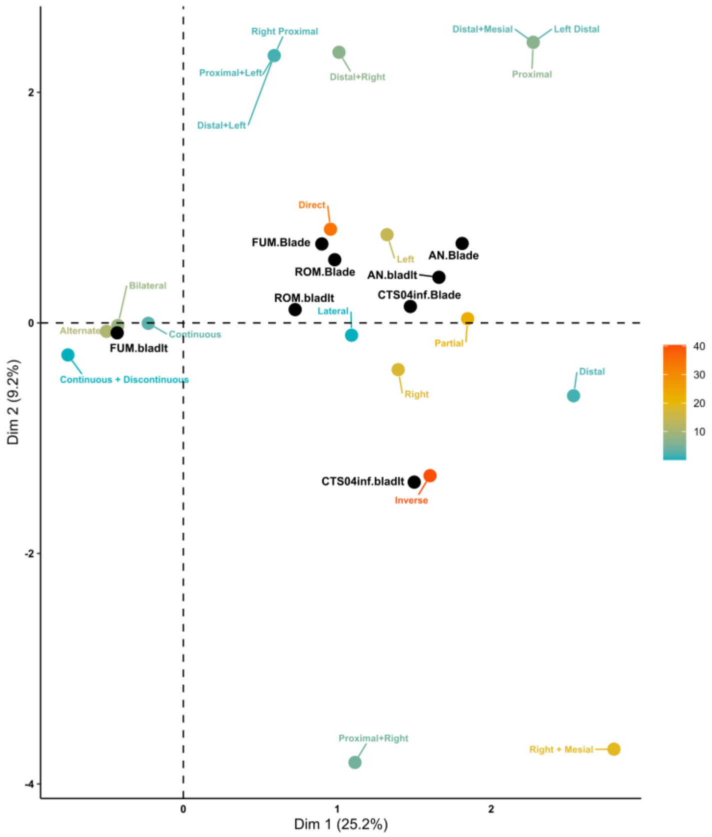

Fig 11. ***Retouch domain MCA biplot of EUP assemblages.*** *The active variables are coloured from light blue to dark orange according to their total contribution to the two dimensions. The supplementary qualitative categories are coloured in black.*

Discussion

The production of laminar implements during the Upper Palaeolithic typically relies on volumetric cores knapped with marginal direct percussion (Pelegrin, 2011, 1995). However, detailed analysis and reconstruction of the knapping process reveal subtle differences. The Solutrean laminar products appear to have been produced using slightly different procedures than those reconstructed for Early Upper Paleolithic (Aubry et al., 2007; Bachellerie, 2022; Zilhão, 1997). This study is among the first to compare combined sets of categorical and numerical lithic attributes from assemblages attributed to different Upper Palaeolithic technocomplexes. It examines their collective variation on a continuous scale using MCA. Below, we will first reflect on the MCA's ability to highlight variation within Upper Palaeolithic laminar productions. Then, we will assess its effectiveness in detecting more subtle variations when focussing on the Early Upper Palaeolithic. Finally, we will look into the interest of MCA analysis to better understand the role of bladelets in the lithic productions of the EUP.

Identifying subtle patterns of variability is therefore highly significant, emphasising the importance of conducting quantitative analyses of technologically relevant attributes to uncover nuanced patterns of variation. As we have shown the MCA managed to provide meaningful association between the active variables and the supplementary categories and to display structures in the data that suggest EUP technological patterns.

Capturing variability using MCA within the Upper Palaeolithic

We hypothesise that the studied EUP assemblages would be more similar to one another than to any other Upper Paleolithic assemblages, assuming that technocomplexes close in time, like those grouped in the EUP, would share more technological traits than non-contemporary technocomplexes. Our MCA technological results support this view. Both within the Platform domain (Fig. 7) and the Convexity domain (Fig. 9), the Solutrean blanks cluster closely together. In contrast, the Protoaurignacian and Southern Ahmarian assemblages are more closely related to each other than either is to the Solutrean. The Protoaurignacian and Southern Ahmarian assemblages are strongly associated with more slender blanks and punctiform or linear platforms, while the Solutrean assemblages are predominantly associated with thicker blanks (relative to their width) and cortical platforms.The Solutrean technocomplex also clusters separately from the EUP, particularly in terms of core convexity shaping and the centrality of knapping on the flaking surface. While the EUP assemblages, especially the Southern Ahmarian, tend to cluster toward off-axis morphologies, torsion, and plunging distal terminations, the Solutrean assemblages are more characterised by on-axis, convergent, and feathered profiles. Furthermore, although no MCA comparison is possible between the EUP and Solutrean assemblages due to the lack of retouch attributes in the Solutrean dataset, the retouch patterns of EUP blades and bladelets are more similar to each other than to those of the Solutrean. In the Solutrean, retouch often transforms blanks into backed, shouldered, stemmed, and winged points (see details in (Cascalheira, 2019)), rather than the lateral retouch typical of the EUP.

Capturing variability using MCA within the EUP

Our second hypothesis tested whether there is a consistent association between the assemblages classified in one EUP facies, hence testing the validity of keeping separate the various EUP assemblages according to their traditional taxonomy. Both the Platform (Fig 8) and Convexity (Fig 10) domains do not show a strong association between assemblages attributed to the Protoaurignacian and isolation of the only Southern Ahmarian assemblage. The Platform domain shows a separation according to geographical gradient, with the ROM and AN assemblages mostly laying in the upper quadrants of the biplot, while FUM and CTS04inf assemblages lie in the lower quadrants. Nevertheless, all the assemblages are mostly clustered around the dimensions' origins, hence showing a low degree of difference. Also, we must notice that plain, punctiform, and linear platforms, despite being a widely accepted terminology in platform description are rather void of meaning if not accompanied by more objective attributes, such as platform measurements. Effectively, the biplot confirms the common knowledge about the EUP assemblage and the exploratory plots: EUP assemblages rarely prepare the striking platforms. To further expand this line of research, it would be useful to include Early Aurignacian assemblages in the analysis, as faceting is commonly witnessed in blade production (Bon, 2002; Bordes, 2005; Le Brun-Ricalens, 2005). The Convexity domain shows a differentiation according to the blanks category and not a clustering of different technocomplexes. This aspect will be dealt more with in the following paragraph. Whether patterns of differentiation within the EUP exist they might be highlighted by attributes reflecting stylistic and functional choices: for example, retouching. The EUP features mostly a various array of laterally retouched bladelets. The most indicative features are the position, localisation, and distribution of retouch identifying them as Dufour bladelets, Font-Yves points, and el-Wad points (Bar-Yosef and Belfer-Cohen, 1977; Garrod, 1957; Kuhn and Stiner, 1998; Laplace, 1966; Le Brun-Ricalens et al., 2009). Through our analysis (Fig 11), we show there is a degree of difference between the assemblages in terms of the way blades and bladelets are retouched. FUM is strongly correlated with the classic definition of Dufour bladelets, instead, CTS04inf bladelets show a strong correlation with the inverse position, therefore signifying they mostly correlate with Dufour bladelets. In an earlier comparative study, the prevalence of inverse retouch on Les Cottés Protoaurignacian bladelets and the prevalence of alternate retouch on Grotta di Fumane A1-A2 bladelets was already evident (Falcucci et al., 2018). Instead, blades from FUM, ROM, and CTS04inf are mostly related to the direct position. Also, ROM bladelets mostly correlate with direct retouching, despite the presence of Dufour and Pseudo-Dufour bladelets in the assemblage (Chu et al., 2022). Blades and bladelets from AN correlate more with the direct and partial retouch. Earlier work showed that the el-Wad point is a rather unstandardised type (Le Brun-Ricalens et al., 2009) and that retouch does not follow a particular configuration in distribution and localisation (Gennai et al., 2023).

Gennai and colleagues (Gennai et al., 2021) suggested that technological attributes do not support different technocomplexes, but a strong degree of similarity between EUP assemblages in terms of technological behaviour. The present analysis confirms this suggestion, at least for the compared assemblage, in fact, the Al-Ansab AH 1 assemblage fits well within the Protoaurignacian assemblages' variability. Instead, our new results on retouch patterns might shed some light on the regionalisation, or perhaps internal chronological evolution, of the EUP. The current hypotheses of the EUP dispersal are rather in agreement with each other with a rapid, east-to-west movement (Barshay-Szmidt et al., 2018; Floss et al., 2016; Higham et al., 2012; Mellars, 2011; Shao et al., 2024). Contra this narrative, Chu suggested a less direct pattern of dispersal, especially regarding the Carpathian Basin (Chu, 2018; Chu et al., 2022). Our findings could be consistent with either a rapid dispersal of human groups carrying a coherent technological set that endured relatively unaltered for millennia, or with ongoing interactions within this geographical and temporal expanse.

Future studies involving broader comparative datasets and refined chronological frameworks are essential for addressing these debates.

The role of bladelets in the EUP reduction process

Inevitably, one topic of our analysis is whether Palaeolithic archaeologists should attribute bladelets, a rather uncommon blank type before the onset of the Upper Palaeolithic (Kadowaki et al., 2024), importance within the reduction process There is plenty of research on the role of bladelets and its importance in defining the transition to new behaviours and social organisations. For example, Bon (Bon, 2002) and Teyssandier (Teyssandier et al., 2010) suggested a different role for bladelets in the Protoaurignacian and the following Early Aurignacian: within the first one bladelets are the result of core reduction, while in the latter are produced from specialised small cores. The Southern Ahmarian follows the same Protoaurignacian process: the core is eventually reduced and therefore it produces smaller blades, the bladelets (Goring-Morris and Davidzon, 2006; Monigal, 2003; Parow-Souchon et al., 2021). Though new research suggested that bladelets are not the product of core shrinkage, they are actively sought as target products in Protoaurignacian and Early Southern Ahmarian contexts (Bataille et al., 2018; Falcucci et al., 2017; Gennai et al., 2023, 2021). They also form the bulk of the most recognisable retouched tool types within the Aurignacian: Dufour bladelets and Font-Yves bladelets (Laplace, 1966). Yet, the 12 mm width threshold traditionally used to differentiate blades from bladelets is an empirical standard that has been widely applied but rarely assessed. Here we will reflect on how and if MCA can help to assess this 12 mm threshold and hence test the strength of this parameter used to distinguish blade from bladelets during the Palaeolithic.

The Convexity domain (Fig 10) shows a neat division between the blades and bladelets of the EUP assemblages. Instead, the Solutrean blades and bladelets are well associated with each other, witnessing a strong similarity across the different sizes (Fig 9). EUP Bladelets align with attributes like feathered, on-axis, convergent, and straight signifying they mostly belong to target production phases. Instead, blades tend to split between those featuring an asymmetric cross-section and slightly curved profile (AN and ROM) and those showing polyhedric cross-section and parallel outline (CTS04inf and FUM). This confirms the earlier classical analysis. In AN and ROM bladelets tend to be identified as coming from target production phases, while blades split between management and target (Gennai et al., 2021). In general, bladelets are more regular and elongated than blades (Falcucci and Peresani, 2022) but there is some degree of overlapping between blades and bladelets (Falcucci and Peresani, 2022; Lombao et al., 2023). This is mirrored by the Convexity domain results, in fact FUM blades are closer to regular, on-axis morphologies, but nevertheless also to curved profiles. Such emphasis on bladelets within the EUP is also demonstrated by the specific treatment they received in FUM and CTS04inf retouch patterns. Instead, in ROM and AN the retouch pattern is rather unspecialised. Our MCA analysis is then a good indicator that the 12 mm width threshold between blades and bladelets has a heuristic meaning in the EUP technology.

Conclusions

With this paper, we would like to affirm the importance of lithic studies and transparent methodologies of investigation to reconstruct past human behaviours and major anthropological events, like one of the *Homo sapiens* dispersals. Technological studies play a pivotal role in complementing genetic research. While DNA studies offer insights into migration patterns, and interbreeding events, lithic analyses provide tangible evidence of cultural transmission, adaptation, and ecological interactions (Hussain and Soressi, 2021; Posth et al., 2023; Tostevin, 2012). For instance, the shared technological traits between the Southern Ahmarian and Protoaurignacian may corroborate the hypothesis of shared genetic ties between Europe and SW Asia at the time. It also reflects aDNA evidence showing distinct genetic traits during the Aurignacian (Posth et al., 2023).

The reproducible methodology employed in this study, including the open sharing of datasets and analytical workflows, sets a precedent for future interdisciplinary research. It is part of a broader movement in Palaeolithic archaeology aimed at improving reproducibility and data-sharing (Pargeter et al., 2023; Reynolds and Riede, 2019; Riede et al., 2024, 2020). Our analysis addressed key topics of debate for the reconstruction of Early Upper Palaeolithic behaviours, such as the similarity between technocomplexes and the role of bladelets within the reduction process. Our analysis demonstrates technological similarity between the Protoaurignacian and the Southern Ahmarian.

Whether this is the results of phyletic evolution, exchanges or independent developments would require more integration of cultural and genetic data. Current radiometric dating is too coarse to assess infra-millennial developments around 40 ka cal BP. The Southern Ahmarian looks younger than the Protoaurignacian (SI file 1), but we need to consider the considerable efforts in modern radiometrically dating the European contexts, that produced older dates (Higham, 2011; Higham et al., 2009). As lithic technologists, we notice that both technocomplexes show a similar attitude towards bladelet production and that bladelets are seemingly more standardised than blades. This standardisation is emphasised by the specific retouch patterns of bladelets in the Les Cottés 04 inférieur and Grotta di Fumane A1-A2 assemblages. Furthermore, these retouch patterns are possibly indicating differences within the analysed EUP assemblages. These differences might be related to functionality, but also by chronological or geographical dynamics.

As we continue to refine and expand the technological and genetic evidence, we move closer to constructing a holistic narrative of the Upper Palaeolithic transition and the spread of modern humans across Eurasia.

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Cottés were allowed by the cave owner, J. Bachelier and C.-H. Bachelier, and excavation permits were issued by the Service regional de l’Archéologie d’Aquitaine. We thank J. and C.-H. Bachelier for allowing us to curate the collection excavated by us on their land.

Data availability statement

The datasets generated and analysed in this study are available in the associated research compendium on GitHub: https://github.com/ArmandoFalcucci/EUP_Comparison. The repository includes all R scripts and derived data required to reproduce the results and figures of the study.

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