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Ex Oriente Lux? A quantitative comparison between northern Ahmarian and Protoaurignacian

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ABSTRACT

The appearance of the Protoaurignacian in Europe around 42,000 years ago is widely believed to result from a major dispersal of anatomically modern *Homo sapiens* out of the Levant, a view primarily supported by perceived similarities between Mediterranean Protoaurignacian and Levantine Ahmarian stone tools. However, no quantitative technological comparison has yet thoroughly tested this connection. Here, we present the first systematic evaluation of lithic technology from Protoaurignacian assemblages in Italy and from the northern Ahmarian and post-Ahmarian layers at the reference sequence of Ksar Akil (Lebanon). Using attribute analysis and multivariate statistics, we assessed technological similarities and differences across different stages of the core reduction sequence. Our results demonstrate very limited affinities and distinct technological trajectories between the two regions. While the northern Ahmarian at Ksar Akil is characterized by bidirectional volumetric core reduction aimed at blade production, the Protoaurignacian exhibits a strong emphasis on bladelet production from unidirectional cores. Although lithic miniaturization trends are observed in both regions, the post-Ahmarian layers at Ksar Akil primarily produced twisted bladelets from burins and carinated cores—a feature uncommon in the Protoaurignacian. These findings challenge the hypothesis of a Levantine origin for the Protoaurignacian and, more broadly, suggest that technological convergence—driven by the growing importance of multicomponent projectile technology and increased mobility—played a central role. Thus, our study underscores the need to reconsider diffusionist explanations and emphasizes the central role of internal cultural innovation among foraging groups settled in different regions of the Old World in shaping the emergence of the Upper Paleolithic.

1. Introduction

1.1. Biocultural perspectives on Upper Paleolithic research in the Old World

The movements of people across landscapes and the spread of technological innovations have captivated archaeologists since the field began. The European subcontinent is often viewed as the westernmost terminus of several east-to-west diffusion waves of African *Homo sapiens* occurring between approximately 55 and 40 ka (McDougall et al., 2005; Hublin et al., 2017; Scerri et al., 2018; Meneganzin et al., 2022; Vidal et al., 2022; Finlayson et al., 2023; Scerri and Will, 2023), or even earlier (Harvati et al., 2019). Due to its strategic geographic location, the Levant is recognized as a critical biogeographic corridor facilitating these dispersal events (Bosch et al., 2015; Abbas et al., 2023). These events are believed to have ultimately contributed to the final demise of late Neanderthals through complex processes involving environmental disruptions, competitive exclusion, and assimilation (Trinkaus, 2007; Banks et al., 2008; Villa and Roebroeks, 2014; Wolf et al., 2018; Vidal-Cordasco et al., 2022; Li et al., 2024).

Just as dispersals are cited to explain changes in material culture, certain industries or technological variants are thought to map the presence and expansion of distinct hominin populations. Due to the scarcity of human remains associated with Initial Upper Paleolithic (IUP) and Early Upper Paleolithic (EUP) technocomplexes (Finlayson et al., 2023; Zilhão et al., 2024), archaeologists have relied primarily on similarities in material culture to trace the dispersal of anatomically modern *Homo sapiens* (amHs) groups across Eurasia (Hublin, 2015). Many scholars claim that the

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changes observed in the European archaeological record at the onset of the Upper Paleolithic are linked to the more or less successful dispersals of amHs into Europe, with the Levant often cited as the source of ancestral industries and cultures (Anderson et al., 2015; Hublin, 2015; Slimak, 2023).

This approach has been applied to the IUP and its various subgroups, including the Bachokirian (Hublin et al., 2020), the Bohunician (Skrdla, 2003; Tostevin, 2003), and the Neronian (Slimak et al., 2022), as well as to EUP assemblages such as the Lincombian-Ranisian-Jerzmanowician (Demidenko and Škrdla, 2023) and the Châtelperronian (Slimak, 2023). The most widely accepted hypothesis linking a European Upper Paleolithic industry to a Levantine predecessor proposes that the earliest phase of the Aurignacian technocomplex in Europe—commonly referred to as the Protoaurignacian (PA)—originated from the Levantine Ahmarian (Hublin, 2015; Zilhão et al., 2024).

Many in the field have begun to doubt the soundness of attributing Paleolithic technocomplexes to a single hominin taxon during a period when populations are known to have been interacting in various ways. While a handful of IUP and EUP assemblages are associated with bone and/or dental remains morphologically or genetically assigned to amHs (Benazzi et al., 2011, 2015; Hublin et al., 2020; Slimak et al., 2022; Gicqueau et al., 2023; Mylopotamitaki et al., 2024; Sümer et al., 2025), an increasing number of scholars question the methodological and interpretative background of such results (Finlayson et al., 2023; Zilhão et al., 2024). The uncertainty of using archaeological cultures as proxies for hominin taxa is compounded by biomolecular and genetic evidence showing clear signs of genetic admixture between autochthonous Neanderthals and amHs in Eurasia (Green et al., 2010; Prüfer et al., 2014, 2017, 2021; Fu et al., 2015, 2016; Slon et al., 2018; Bergström et al., 2021; Hajdinjak et al., 2021; Harvati and Ackermann, 2022; Sümer et al., 2025), bolstering earlier studies showing the anatomically mosaic features of early European amHs fossil remains from Oase in Romania (Trinkaus et al., 2003; Soficaru et al., 2007), Mladeč in Czech Republic (Teschler-Nicola, 2006), and Lagar Velho in Portugal (Zilhão and Trinkaus, 2002). Because admixture was more the rule than the exception, it has been suggested that the rigid dichotomy between species (e.g., amHs and Neanderthals) may obscure underlying biocultural processes evident in the archaeological record (Teyssandier, 2024).

We argue that these processes could be better understood by analyzing biological data and cultural dimensions of human evolution separately (Kuhn, 1995). This separation would facilitate the exploration of cultural evolutionary dynamics and enable a more parsimonious examination of alternative scenarios involving demic diffusion, cultural transmission, and/or convergence. Such an approach is particularly relevant in studies of the EUP, where the cultural diversification accelerates significantly, prompting the classification of technocomplexes into both chronological and geographic subgroups. This is even true for the Aurignacian, which has historically been labeled as the main proxy for the pioneering colonization of Europe by amHs (Davies, 2001; Grimaldi et al., 2014; Anderson et al., 2015; Hublin, 2015). Even today, due to its wide geographic distribution and long temporal span, the Aurignacian is regarded as representative of the most successful amHs dispersal event (Djakovic et al., 2024).

1.2. Revisiting the Levantine origin of the Protoaurignacian

The origin of the PA from the Levantine Ahmarian was first proposed based on perceived morphological affinities in lithic projectile implements (Bar-Yosef, 2003; Mellars, 2004, 2006a, 2009). The sites that played a crucial role in shaping these ideas include Ksar Akil in Lebanon, the reference sequence for the Levantine late Pleistocene (Bergman et al., 2017), and Grotta di Fumane in northeastern Italy (Peresani, 2022). Over time, this hypothesis gained traction due to the seeming absence of possible ancestral industries in Europe characterized by the production of elongated implements—such as blades and bladelets from volumetric cores—and the supposed earlier chronological appearance of the Ahmarian (Mellars, 2006a, 2006b; Teyssandier, 2006; Zilhão, 2006, 2007, 2013; Bar-Yosef, 2007; Hoffecker, 2009; Tsanova et al., 2012, 2024; Hublin, 2015; Roussel et al., 2016; Alex et al., 2017; Zilhão et al., 2024). Similar observations have been made for coeval industries such as the Baradostian in the Zagros Mountains of Iran (Tsanova, 2013; Ghasidian et al., 2019).

Recent developments raise several concerns with what has now become a consensus view about the origins of the PA. First, the PA cannot be regarded as the earliest laminar-based industry in Europe. The Châtelperronian—dated to approximately 44 to 40 ky cal BP and primarily distributed in southwestern France and northern Spain (Djakovic et al., 2022, 2024)—also emphasizes the production of laminar blanks from volumetric cores (Roussel et al., 2016). The authorship of the Châtelperronian has been the subject of intense debate (Bar-Yosef and Bordes, 2010; Welker et al., 2016) as its presumed exclusive association with Neanderthals has been challenged (Gicqueau et al., 2023; Teyssandier, 2024), while proposed technological links to the preceding Mousterian industry have largely been dismissed (Bordes and Teyssandier, 2011; Gravina et al., 2018). Interestingly, Djakovic et al. (2022) noted a chronological overlap between PA and Châtelperronian assemblages, with recent reassessments dating the earliest PA sites to as early as 43 ky cal BP in the French Pyrenees, the Rhône Valley, and the Liguro-Provençal arc (Barshay-Szmidt et al., 2018; Frouin et al., 2022; Slimak et al., 2022; Berlioz et al., 2025).

Meanwhile, available chronological evidence from the Levant provides conflicting information about the timing of the Ahmarian. Early dates from sites such as Kebara Cave (Rebollo et al., 2011) and Manot Cave (Alex et al., 2017) have come under serious scrutiny (Zilhão et al., 2024). The early determinations at Kebara, between 47 and 46 ky cal BP, are problematic due to erosion of Mousterian deposits, which could have resulted in mixing with Ahmarian layers (Goldberg, 2007; Zilhão, 2013). Similarly, postdepositional processes have been identified at Manot (Berna et al., 2021), along with issues related to the integrity of stratigraphic units and the arbitrary classification of certain lithic components as either Ahmarian or Levantine Aurignacian (Abulafia et al., 2021). At Ksar Akil, chronological assessments have yielded conflicting results (Douka et al., 2013; Douka, 2013; Bosch et al., 2015), while the Ahmarian sequence at Üçağızlı provides much younger dates (Kuhn et al., 2009; Douka, 2013). Overall, radiocarbon dating of Levantine Upper Paleolithic sites is particularly challenging due to poor collagen preservation (Bosch et al., 2015), further complicating the alignment of these timelines.

Even if the authorship and chronological framework of the industries remains uncertain, scholars often treat Ahmarian and PA as synonymous, representing a single cultural phenomenon with uniform behavioral and technological systems (Bar-Yosef, 2003; Teyssandier et al., 2010; Zilhão, 2013, 2014; Goring-Morris and Belfer-Cohen, 2018). The assumption that the PA and the Ahmarian are typologically and technologically indistinguishable positions the Ahmarian as the direct source of the PA (Zilhão et al., 2024) and hence as evidence of population dispersal or other long-distance connections. However, hypotheses about the relationship between the PA and the Ahmarian have relied mainly on impressionistic observations of similarities rather than detailed technological analyses. These assumptions are further undermined by the presence of significant internal variation within the

Ahmarian. For example, studies have revealed notable differences in lithic technology between Ahmarian assemblages from the northern and southern Levant (Bergman, 1988; Davidzon and Goring-Morris, 2003; Kuhn et al., 2003; Marks, 2003; Mellars, 2009; Tsanova et al., 2012; Kadowaki et al., 2015; Abulafia et al., 2021; Gennai et al., 2023; Slimak, 2023).

The Ahmarian is one of the most extensively studied technocomplexes of the Levant. Its name originates from the rockshelter of Erq el-Ahmar in the Judean Desert, where archaeologists identified assemblages characterized by backed points on blades and bladelets (Neuville, 1934; Garrod, 1957; Gilead, 1991). Gilead (1981) later expanded the term to describe lithic assemblages in the Sinai region, which postdate the IUP (i.e., the Emiran) and precede flake-dominated assemblages such as the Levantine Aurignacian, Arkov-Divshon, and Atlitian (Goring-Morris and Belfer-Cohen, 2003; Shemer et al., 2023). In this study, we use the term Ahmarian rather than Early Ahmarian as the so-called Late Ahmarian is now considered a distinct entity under the term Masraqan (Hussain and Richter, 2015; Goring-Morris and Belfer-Cohen, 2018). Currently, the Ahmarian is divided into a northern and a southern variant. Key sites for the northern Ahmarian include Ksar Akil, Kebara, Üçağızlı, Qafzeh, Yabrud II, and Manot, while the southern Ahmarian is described at Abu Noshra, Al-Ansab 1, Boker A, Lagama, Nahal Nizzana XIII, and Tor Sadaf (Goring-Morris and Belfer-Cohen, 2018) (Fig. 1). These geographical groups exhibit notable technological differences, particularly in the methods of laminar production. The northern Ahmarian is characterized by bidirectional core reduction strategies, producing wider and longer blanks (Kuhn et al., 2009; Abulafia et al., 2021), whereas the southern variant primarily employs unidirectional core reduction strategies, yielding slender blanks from narrow-fronted cores (Davidzon and Goring-Morris, 2003; Gennai et al., 2023).

While the southern and northern Ahmarian are often associated with distinct environmental settings—specifically, the Mediterranean biome in the north and the Saharo-Arabian biome in the south (Richter et al., 2020)—archaeological evidence has also led to the hypothesis of internal chronological variability. The southern Ahmarian is now considered to be younger than the northern variant (Kadowaki et al., 2015). Within this framework, some scholars have proposed that the stratigraphic sequence at Ksar Akil reflects a technological shift from the northern to the southern Ahmarian (Bergman et al., 2017; Slimak, 2023). Additionally, an assemblage with characteristics supposedly similar to the southern Ahmarian has been identified as far north as Wadi Kharar 16R in Syria (Kadowaki et al., 2015). These findings are significant because several scholars have observed that the PA more closely resembles the southern Ahmarian than the northern variant (Demidenko and Hauck, 2017; Gennai, 2021; Slimak, 2023). Mellars (2006a) also discussed this from a typological perspective, comparing retouched bladelets from Boker A (Jones et al., 1983) and layers IX–XI at Ksar Akil with those of the PA.

1.3. Establishing a framework for quantitative comparison of Ahmarian and Protoaurignacian

Recent chronostratigraphic and archaeological findings summarized above emphasize the need to critically reconsider the Levantine roots of the PA and particularly its connection with the northern Ahmarian. Despite the broad acceptance of this

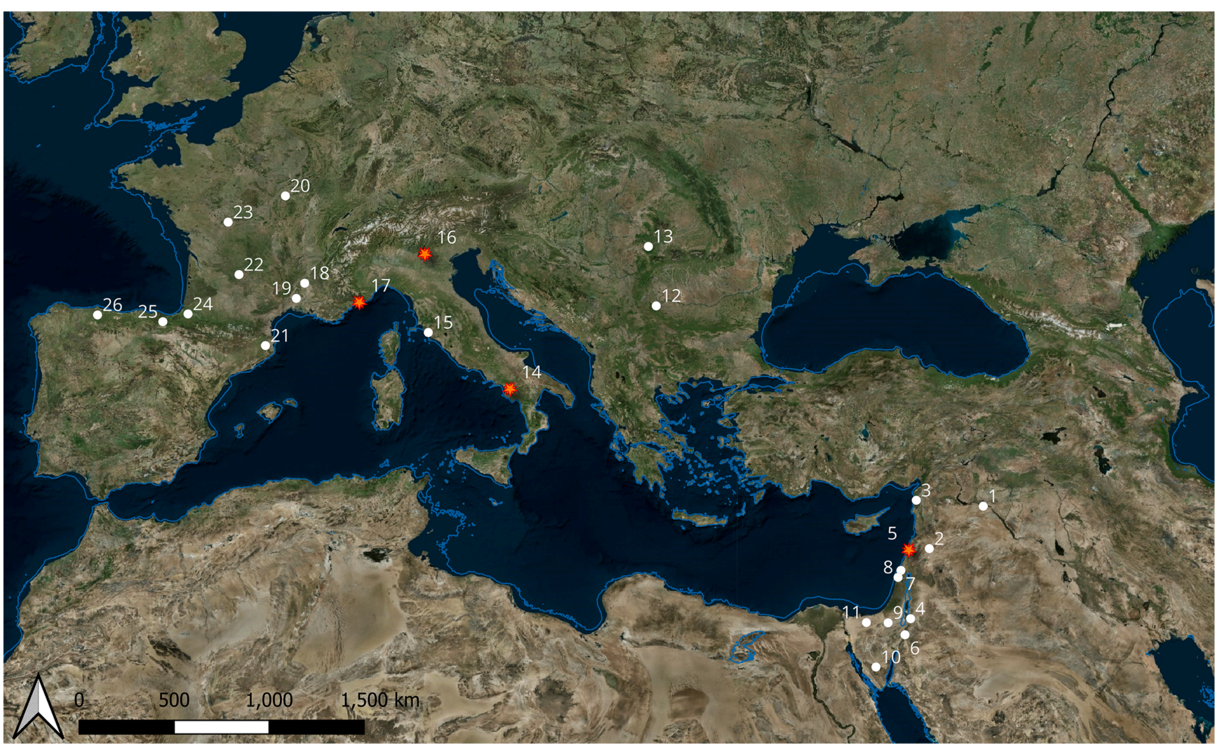

Figure 1. Map of the Mediterranean Basin showing the geographic location of the sites analyzed in this study (red stars): Ksar Akil (5), Grotta di Castelcivita (14), Grotta di Fumane (16), and Riparo Bombrini (17). The map also includes Ahmarian, post-Ahmarian, and Protoaurignacian sites referenced in the paper (white dots). Northern Ahmarian and post-Ahmarian: Yabrud II (2), Ksar Akil (5), and Manot (7); northern Ahmarian: Üçağızlı (3) and Kebara (8); post-Ahmarian: Wadi Kharar 16R (1); Protoaurignacian: Kozarnika (12), Românesti Dumbravita (13), Grotta di Castelcivita (14), Grotta della Fabbrica (15), Grotta di Fumane (16), Riparo Bombrini and Riparo Mochi (17), Grotte Mandrin (18), Esquicho Grapaou (19), Grotte du Renne, Arcy sur Cure (20), L'Arbreda (21), Le Piage (22), Les Cottés (23), Isturitz (24), Labeko Koba (25), and La Viña (26); southern Ahmarian: Tor Sadaf (4), Al-Ansab 1 (6), Nahal Nizzana XIII and Boker A (9), Abu Noshra sites (10), and Lagama sites (11). The map includes a blue line representing the reconstructed mean sea level at −65 m relative to the present-day sea level, based on the Paleocoastlines GIS dataset (https://crc806db.uni-koeln.de/dataset/show/paleocoastlines-gis-dataset1462293239/). The map was generated in QGIS v. 3.28. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

hypothesis, detailed comparisons between PA and Ahmarian lithic technologies are extremely rare. Since lithics are the by-products of learned behaviors—requiring extended teaching and learning processes to transmit the necessary knapping skills and gestures—they preserve crucial information for finely quantifying technological similarities and differences across consecutive stages of the core reduction sequence (Tostevin, 2019). This intrinsic quality of lithic technology has allowed scholars to explore the role of demography and cultural transmission in explaining commonalities among lithic assemblages dated to similar timeframes. For example, it has been suggested that replicating consistent procedures throughout the core reduction process requires prolonged exposure to the entire operational sequence. Transmission of procedures like these is more likely to occur when learners have long-term contact with models (Tostevin, 2007).

Interactions between foraging groups should be understood as part of a continuum of social possibilities (Bettinger et al., 2015), with varying degrees of intimacy influencing the extent of technological similarities in core reduction strategies. Scholars have argued persuasively that, when other confounding factors are accounted for (Cascalheira, 2019), similarities across multiple stages of the core reduction process—from the initial shaping of the raw material nodules to the production of the intended tool forms—serve as strong evidence of cultural relatedness among toolmakers (Nigst, 2012; Tostevin, 2013; Scerri et al., 2014; Cascalheira, 2019). Within this framework, technological convergence can be interpreted as either the result of independent innovation or exposure to limited segments of the reduction sequence. Toolmakers may independently develop similar procedures when attempting to create specific tool types and forms (Tostevin, 2013; Groucutt, 2020). However, independent innovation is unlikely to generate high similarity across multiple stages of the reduction process (Abdolahzadeh et al., 2025). Therefore, a thorough quantitative analysis of lithic assemblages, grounded in a technological approach, provides a more reliable means of assessing cultural relatedness, as opposed to relying solely on typological comparisons.

The goal of this study is to move beyond the impressionistic evidence surrounding the relationship between the Ahmarian and the PA by quantitatively comparing, for the first time, the northern Ahmarian and post-Ahmarian layers at Ksar Akil with some of the earliest PA assemblages in Europe, located south of the Alps and along the Italian Peninsula. We employ a multivariate, assemblage-based approach to quantify similarities and differences in lithic traits across various domains of stone tool production. This approach enables us to capture and assess variability throughout the core reduction sequences. The lack of a quantitative approach has hindered the formulation of compelling scenarios regarding the processes that shaped the archaeological record across the Mediterranean Basin. A renewed focus on the systematic quantification of similarities and differences between lithic assemblages holds the potential to open new avenues for future research. By incorporating the post-Ahmarian layers, we aim to gain further insights into the development of the Upper Paleolithic at Ksar Akil, particularly in relation to its association with the southern Ahmarian.

2. The northern Ahmarian and post-Ahmarian sequence at Ksar Akil

Ksar Akil is a limestone rockshelter located in the Antelias Valley within the Lebanon Mountain range, approximately 10 km from Beirut and around 3 km from the current Mediterranean coastline. A detailed account of the site's excavations and research history is provided by Frahm and Tryon (2019). The site was discovered in 1922 by looters, but formal archaeological excavations began only in 1937, led by American Jesuits Doherty and Murphy from Boston College and Ewing from Fordham University (Murphy, 1938, 1939). During the first two field seasons (1937–1938), their teams excavated a stratigraphic sequence of about 19 m near the looters' pit, which was used to define geological layers followed throughout the excavation (Frahm and Tryon, 2019). After a pause caused by World War II, excavations resumed in 1947–1948 under Ewing's direction, reaching bedrock at a depth of 22.6 m (Ewing, 1947, 1949). Between 1969 and 1975, J. Tixier conducted further excavations, reaching a depth of 9 m. However, due to political instability in the region, Tixier was unable to access the lower EUP layers (Tixier, 1970, 1974; Tixier and Inizan, 1981).

The excavations from both the 1937–1938 and 1947–1948 campaigns (Fig. 2b) followed a grid system of 16 2- by 2-meter squares. The grid was organized with alphabetic markers for the east-west axis and numerical markers for the north-south axis (Fig. 2c). Geological layers, in some cases up to 2 m thick, served as the basis for stratigraphic divisions. Evidence suggests that excavations in 1947–1948 were conducted with greater stratigraphic precision, with layers subdivided into spits in some areas. Excavators reportedly used dry sieving with medium-sized mesh screens (Murphy, 1938), likely around 2.5 cm (Frahm and Tryon, 2019), which aligns with our analysis of the lithic metric cut-off (see below). Lithic artifacts, including bladelets, were more systematically collected in 1947–1948, along with faunal remains (Bosch et al., 2015). However, Murphy (1939) noted that selective discard was common during the excavations, making it difficult to assess the full extent of material recovery.

Ksar Akil contains one of the richest and deepest archaeological sequences in the Levant, with 37 geologically defined layers spanning several cultural phases (Fig. 2a). These include the Middle Paleolithic (layers XXXVII–XXVI), the IUP (XXV–XXI), the northern Ahmarian (XX–XVI), the Upper Paleolithic *sensu lato* (XIII–VI), and the Epipaleolithic (V–I). Detailed studies of the site's assemblages have primarily focused on materials from the 1937–1938 excavations housed at the British Museum in London (e.g., Azoury, 1986; Bergman, 1987; Ohnuma, 1988; Leder, 2016, 2018). The IUP layers are characterized by the use of pyramidal cores and core faceting to produce elongated blanks by hard hammer percussion (Azoury, 1986; Leder, 2016), while the progressive shift to the northern Ahmarian technological system in layer XX has been interpreted as evidence of local technological development (Ohnuma, 1988).

Geologically, the Middle Paleolithic layers consist of alluvial deposits. These progressively transition to brownish-gray sediments beginning with the northern Ahmarian. Three cemented layers of angular stones separated by sterile red clay were found at depths of 1.5 m, 10 m, and 15 m. One of these, Stone Complex 2 (layers XV–XIV), seals the northern Ahmarian from the deposits above, while Stone Complex 1 separates the Middle Paleolithic from the IUP. These layers are thought to indicate episodes of environmental instability, possibly linked to increased precipitation during a wet phase. Douka et al. (2013) have suggested that Stone Complex 2 may correspond to Heinrich Event 4, the onset of which is dated to 40.2 ka (Sanchez Goñi and Harrison, 2010).

Due to differences in excavation methods, correlating layers from the 1937–1938 and 1947–1948 campaigns remains challenging. Douka et al. (2013) tested this offset by comparing radiocarbon dates on shells collected during both excavation periods, finding that the materials from the 1947–1948 excavations yielded older dates. This discrepancy has often led researchers to discuss the Ksar Akil sequence in terms of phases rather than

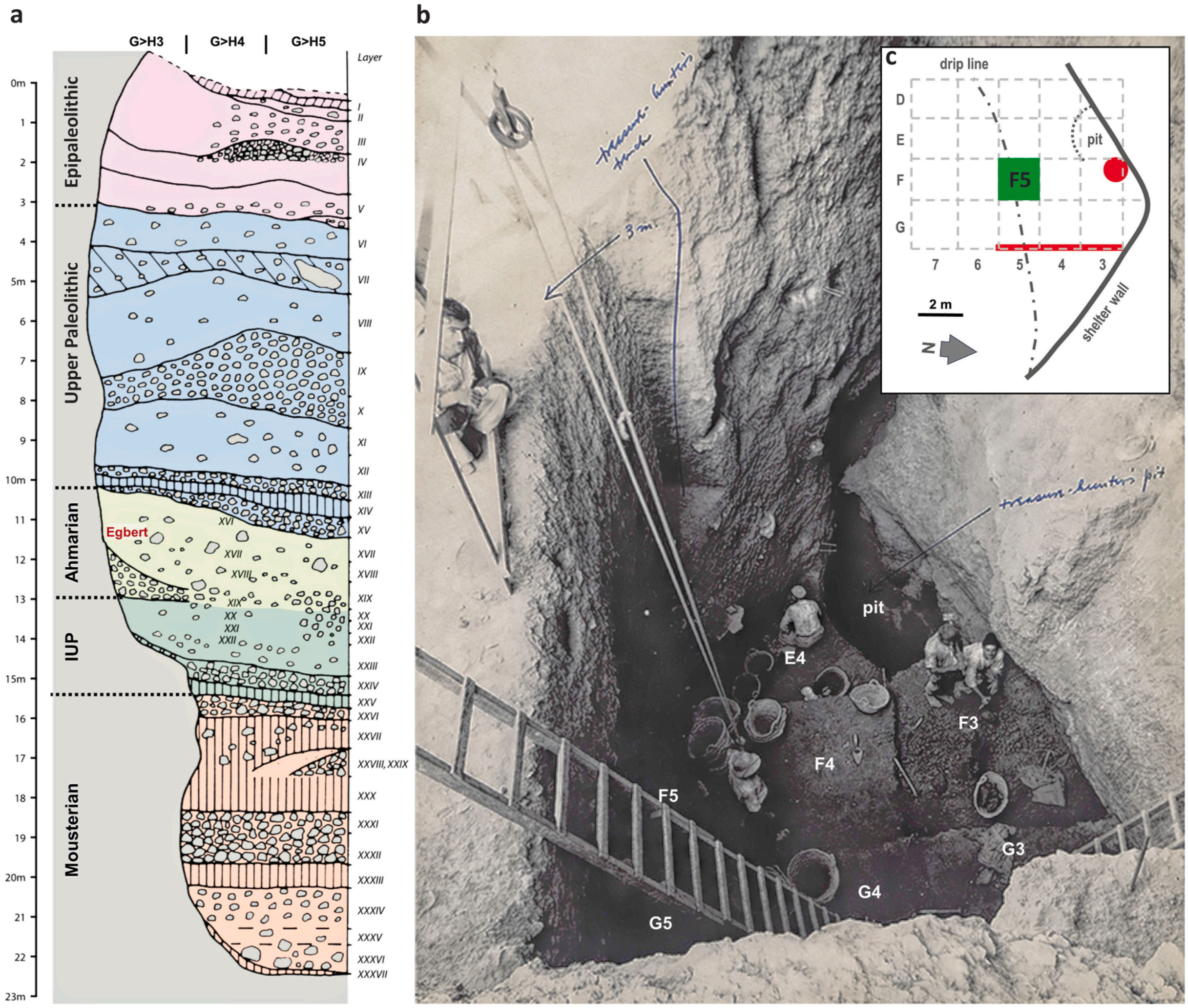

Figure 2. **a.** Stratigraphic sequence of Ksar Akil, illustrating the layers and key technocultural transitions identified. **b.** Photo from ongoing excavations of the Ahmarian deposits in 1938. **c.** Excavation grid (in 2- × 2-m units) with a green square denoting the Unit analyzed in this paper (i.e., F5) and a red circle indicating the burial's location. The figure was modified from Zilhão et al. (2024), incorporating images from Bosch et al. (2015) and Bailey and Tryon (2023). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

stratigraphic units. These phases were summarized by Williams and Bergman (2010) and later refined by Bergman et al. (2017) using data from Tixier's excavations. Table 1 provides an overview of these phases, their cultural attributions, and the proposed technocultural links to the PA according to different scholars.

Some of the most notable findings at Ksar Akil include remains of *H. sapiens* associated with the IUP, northern Ahmarian, and later Upper Paleolithic layers. A maxillary fragment known as 'Ethelruda' was discovered in the IUP layer XXV, while the northern Ahmarian layer XVII yielded the remains of an 8-year-old *H. sapiens* named 'Egbert.' A human tooth was also recovered in the Levantine Aurignacian layer (Tillier and Tixier, 1990). Additionally, a fourth specimen, 'Ksar Akil 4,' found near Egbert's remains, has been identified as *H. sapiens* based on dentition (Bailey and Tryon, 2023). The faunal assemblages have also provided valuable insights. Bosch et al. (2015) observed that the Ahmarian layers were dominated by woodland species, with a more evenly distributed range of taxa than the IUP. The Ahmarian sees an increase in species such as red deer, aurochs, ibex, wild goat, gazelle, wild boar, and spur-thighed tortoise, whereas Mesopotamian fallow deer had been dominant in earlier periods. Additionally, Bosch et al. (2015) noted an increase in marine intertidal gastropods, which were collected and consumed as food, during the Ahmarian.

In the past decade, two independent dating programs have provided differing estimates for the Ahmarian occupations at the site. The first study, focusing on radiocarbon dating of shell beads, concluded that the Ahmarian began around 41.6–40.9 ky cal BP (68.2%) or 40.6–39.9 ky cal BP (68.2%) and ended at 40.1–39.5 ka cal BP or 39–37.5 ka cal BP (Douka et al., 2013). Based on these findings, Douka (2013) argued that the Levant may not have been the origin of the PA, suggesting instead that the region served as a geographic *cul-de-sac* where technologies arrived later than in other regions. A subsequent dating study using gastropods consumed as food obtained significantly older age estimates for the Ahmarian, with differences of approximately 3000 years (Bosch et al., 2015).

It is important to note that shell dating is particularly susceptible to contamination from foreign carbon, primarily due to postmortem diagenetic processes, making it less reliable than charcoal or bone dating. Bosch et al. (2015) suggested that discrepancies between the two studies may be related to sample selection. According to the authors, shells collected for food

Table 1
Stratigraphic correlations between the 1937–1938 and 1947–1948 excavations at Ksar Akil, along with the proposed technocultural phases and their corresponding cultural attributions according to various scholars.

1937–1938 excavations	1947–1948 excavations	Bergman et al. (2017)—phases	Williams and Bergman (2010)	Bergman et al. (2017)—cultural attributions	Slimak (2023)	Kadowaki et al. (2015)	Mellars (2006a, 2009)	Zilhão et al. (2024)	Analyzed in this study
VII–VIII	IXC–XB	VI	5	Levantine Aurignacian	–	–	Levantine Aurignacian	Aurignacian	No
IX	XC	VII	4	Southern Ahmarian affinities	Southern Ahmarian	Southern Ahmarian (Protoaurignacian)	Ahmarian (Protoaurignacian)	Aurignacian	No
X	XIA–XIB	VII	4	Southern Ahmarian affinities	Southern Ahmarian (Protoaurignacian)	Southern Ahmarian (Protoaurignacian)	Ahmarian (Protoaurignacian)	Aurignacian	Yes (XIB)
XI–XIII	XII–XIII	VIII	3	Unassigned	Southern Ahmarian (Protoaurignacian)	–	Ahmarian, XI in 1937–1938 (Protoaurignacian)	Aurignacian	Yes
XIV	XIV	–	–	–	Northern Ahmarian	–	Ahmarian	Aurignacian	Yes
XV	XV	–	–	–	Northern Ahmarian	–	Ahmarian	Aurignacian	No
XVI	XVI	IX	2	Northern Ahmarian	Northern Ahmarian (Châtelperronian)	Northern Ahmarian	Ahmarian	Ahmarian (Protoaurignacian)	No
XVII	XVII	IX	2	Northern Ahmarian	Northern Ahmarian (Châtelperronian)	Northern Ahmarian	Ahmarian	Ahmarian (Protoaurignacian)	Yes
XVIII	XVIII	IX	2	Northern Ahmarian	Northern Ahmarian (Châtelperronian)	Northern Ahmarian	Ahmarian	Ahmarian (Protoaurignacian)	Yes
XIX	XIXA–XIXB	IX	2	Northern Ahmarian	Northern Ahmarian	–	Ahmarian	Ahmarian (Protoaurignacian)	Yes
XX	XX	IX/X	1/2	Northern Ahmarian	Northern Ahmarian	–	Ahmarian	IUP	No
XXI–XXV	XXI–XXV	X	1	IUP	IUP (Neronian)	–	Emiran	IUP	No

The table indicates which phases were analyzed in this study.
IUP, Initial Upper Paleolithic.

consumption may provide more accurate radiocarbon dates since the mollusks likely spent minimal time exposed between death and burial, reducing the risk of contamination. However, both dating programs reported results that were not consistently in stratigraphic order, leading Zilhão et al. (2024) to argue that stratigraphic issues—such as the use of artificial excavation spits and postdepositional artifact migration—primarily contributed to these inconsistencies.

3. Materials and methods

3.1. The Ksar Akil assemblages

This study focuses on the lithic collections from Ewing's 1947–1948 excavations, housed at the Peabody Museum of Archaeology and Ethnology (PMAE) at Harvard University. Although these excavations are often considered more reliable and accurate in terms of stratigraphy than the 1937–1938 field seasons, the Harvard collections have been studied less often (e.g., Iovita, 2009; Williams and Bergman, 2010; Slimak, 2023), making this research timely. One of us (A.F.) conducted data collection over a four-month period. After a preliminary screening and quantification of the available lithics, we prioritized unit F5, which covers an area of 4 m^2, for technotypological analysis. This unit was chosen over another with abundant archaeological content, E5, due to a trench that had partially truncated the E5 area (Williams and Bergman, 2010). Our analysis included lithics recovered from 11 consecutive layers, ranging from layer XX to XIB. However, layers XV and XIV are excluded from this study due to their very small sample sizes and overall composition of the lithic assemblages, which led previous researchers to describe them as nearly sterile (Azoury, 1986; Ohnuma, 1988). All compared assemblages were analyzed by a single individual, ensuring that the recorded attributes are consistent and not subject to known interobserver variation in lithic analysis (Pargeter et al., 2023).

Table 2 provides an overview of the lithics sorted into macroclasses from the analyzed layers (XX–XIB), comprising a total of 5380 artifacts. The distribution of artifacts varies considerably across layers, with more than 1300 lithics recovered from layer XVI, while only 128 artifacts were found in layer XX. Notably, layer XX contains no cores, a fact that could be attributed either to the overall low number of recovered artifacts or the possible loss of this lithic class. In contrast, other layers with fewer artifacts, such as XIII, have a relatively high number of cores. Due to the absence of cores, layer XX will be excluded from the comparative analyses with the PA. Ohnuma (1988) noted that layer XX is difficult to classify technologically, partly because the separation between it and the preceding IUP layer (XXI) was not clearly defined. Lastly, for layer XI, only the lower spit (XIB) was analyzed due to time constraints that prevented the inclusion of XIA in this study.

The majority of artifacts are classified as blanks (unretouched pieces), followed by retouched tools and core-tools. Core-tools—defined as cores that are typologically identifiable as tools (e.g., carinated endscrapers, carinated burins, and burin cores)—are particularly abundant in the upper layers (XIII to XIB). The proportion of cores and tools is notably high compared to that in other stratified cave sites, suggesting selective material discard during excavation, as well as the potential loss of artifacts during the transfer and subdivision of collections. While these issues have been documented for the 1937–1938 collections housed at the British Museum (Williams and Bergman, 2010), our study indicates that similar biases may affect the PMAE collections as well. It is worth noting that Shemer et al. (2024) reported a clear underrepresentation of debitage categories—such as flakes, core-

Table 2
Quantification of the materials from unit F5 at Ksar Akil.

Layer	Blank	Core	Core-tool	Tool	Other	Total
XIB	289 (39.4%)	73 (9.9%)	155 (21.1%)	213 (29.0%)	4 (0.5%)	734
XII	262 (58.6%)	41 (9.2%)	46 (10.3%)	96 (21.5%)	2 (0.4%)	447
XIII	112 (50.0%)	25 (11.2%)	35 (15.6%)	52 (23.2%)	0 (0.0%)	224
XVI	704 (53.7%)	138 (10.5%)	10 (0.8%)	447 (34.1%)	13 (1.0%)	1312
XVII	311 (57.7%)	74 (13.7%)	10 (1.9%)	144 (26.7%)	0 (0.0%)	539
XVIII	219 (50.2%)	59 (13.5%)	7 (1.6%)	149 (34.2%)	2 (0.5%)	436
XIXA	476 (48.4%)	166 (16.9%)	25 (2.5%)	313 (31.8%)	4 (0.4%)	984
XIXB	328 (56.9%)	41 (7.1%)	6 (1.0%)	200 (34.7%)	1 (0.2%)	576
XX	92 (71.9%)	0 (0.0%)	0 (0.0%)	36 (28.1%)	0 (0.0%)	128
Total	2793 (51.9%)	617 (11.5%)	294 (5.5%)	1650 (30.7%)	26 (0.5%)	5380

The category 'Core-tool' includes artifacts that can be typed also as tools (e.g., carinated pieces) as well as cores reused as tools. The 'Other' category includes unworked raw materials as well as possible hammerstones and angular debris.

trimming elements, and cortical items—in the Levantine Aurignacian and Atlitian layers at Ksar Akil too.

We further investigated the integrity of the studied datasets, and a detailed assessment is presented in Supplementary Online Material (SOM) Note 1, along with SOM Tables S1–S10 and SOM Figures S1–S5. Our results, which include a comparison with the IUP and Ahmarian assemblages from Üçağızlı Cave in Turkey (Kuhn et al., 2009), reveal a bias in the PMAE collections toward complete blanks, particularly blades. This bias suggests that artifacts from the optimal phase of core reduction were preferentially retained, while blanks with more than 33% cortical coverage were under-represented. Unretouched flakes were seldom kept, whereas retouched tools were selected irrespective of their specific morphological attributes.

Additionally, smaller laminar blanks (i.e., bladelets) were not consistently recovered in these early excavations at Ksar Akil, likely due to the use of a screen mesh that was too large for effective sediment screening (Williams and Bergman, 2010). This issue particularly affects the uppermost layers, which show an increase in bladelet production. Combined with the results of flake and bladelet quantification, this evidence strongly suggests that some lithic materials were either not recovered or selectively discarded during both early fieldwork campaigns at Ksar Akil. Although the PMAE collections are often described as more complete than those at the British Museum (Williams and Bergman, 2010; Slimak, 2023), it is notable that fragmented blanks were reported at higher frequencies by Ohnuma (1988) in layers XX–XV from units E4–F4 (1937-1938 excavations), compared to our findings—a discrepancy that warrants further exploration.

These findings are crucial for structuring a robust technological comparison between the northern Ahmarian and post-Ahmarian layers at Ksar Akil and the PA. To ensure methodological consistency, the comparison will be based exclusively on complete blades and bladelets, with blanks exhibiting more than 33% cortical coverage excluded from both the Ksar Akil and PA datasets. All shaped tools are included, regardless of completeness or cortex coverage. Similarly, all cores are included, but only those with evidence of laminar production are used for statistical comparisons. Lastly, due to their similar composition and limited artifact counts, layers XIII and XII are merged for the analysis, while layer XX is excluded entirely due to the small sample size and absence of key artifact categories (e.g., cores).

3.2. The Protoaurignacian assemblages and the merged dataset

For this comparative study, we analyzed three assemblages from Italy, retrieved from some of the earliest PA sites in Europe: Grotta di Fumane in northeastern Italy (Falcucci et al., 2017, 2024b; Peresani, 2022), Riparo Bombrini in northwestern Italy (Riel-Salvatore and Negrino, 2018; Holt et al., 2019; Falcucci et al., 2025a), and Grotta di Castelcivita in southern Italy (Gambassini, 1997; Falcucci et al., 2024a). All sites were analyzed by one of us (A.F.), and the corresponding datasets are publicly available in Open Access repositories (CC-BY-4.0 licenses) associated with each site's publications (Falcucci et al., 2024c, 2024d, 2025d). These datasets are particularly suitable for comparison with Ksar Akil because the lithic analyses focused on reconstructing laminar core reduction strategies. Additionally, each assemblage contains a large number of complete blades, bladelets, cores, and tools.

At Fumane, we sampled layers A2 and A1, which are dated between 41.2 and 40.4 ky cal BP (68.2% probability) (Higham et al., 2009; Marín-Arroyo et al., 2023). These layers will be treated as a single analytical unit. A recent lithic taphonomic study found that they form a single stratigraphic unit, with interlayer blade fragment conjoins linking different areas of the excavation (Falcucci et al., 2024b). Areas identified as potentially disturbed (e.g., the innermost part of the cave) have been excluded from the analysis, following the findings of the break connection study and spatial analysis.

At Bombrini, layers A2 and A1 will also be treated as a single analytical unit since no significant technotypological differences were identified by Riel-Salvatore and Negrino (2018) and Falcucci et al. (2025a). These layers cannot be distinguished geologically despite some marked variability in raw material procurement and site-use strategies (Riel-Salvatore and Negrino, 2018; Pothier-Bouchard et al., 2024; Vallerand et al., 2024). The PA at Bombrini is dated between 40.7 and 35.6 ky cal BP (68.2% probability) (Benazzi et al., 2015), although the dating results may have been affected by low amounts of extracted collagen and possible contamination (Frouin et al., 2022).

At Castelcivita, only layer rsa' is included in the analysis as the subsequent layer gic has been attributed to the Early Aurignacian (Falcucci et al., 2024a). The sequence at Castelcivita was sealed by tephra from the Campanian Ignimbrite super-eruption (39.85 ± 0.14 ka; Giaccio et al., 2017), providing a crucial chronological marker. Optically stimulated luminescence (OSL) and radiocarbon dating findings align with the Campanian Ignimbrite age and suggest that the PA at Castelcivita began slightly later than at Fumane and Bombrini. This indicates that PA technological systems reached southern Italy at a later stage (Douka et al., 2014; Higham et al., 2024).

These three PA sites show marked differences in raw material use. Owing to the scarcity of high-quality stone resources, foragers visiting Bombrini relied on exogenous raw materials sourced from regions as far as 400 km away, including the eastern and western Provence of southeastern France, as well as the central Apennines of Italy (Negrino and Riel-Salvatore, 2018; Riel-Salvatore and Negrino, 2018; Falcucci et al., 2025a). The local chert at

Bombrini, from the Ciotti formation, was of variable quality and small size, which led to the production of fewer blades than at Fumane (Bertola et al., 2013). Toolmakers visiting Fumane and Castelcivita primarily utilized locally available raw materials. At Fumane, however, toolmakers had access to the high-quality chert outcrops of the western Lessini Mountains (Venetian Prealps), with nodules and slabs of varying sizes and shapes (Bertola, 2001), while Castelcivita toolmakers exploited chert and radiolarite pebbles, as well as chunks detached from larger blocks with varying internal quality (Gambassini, 1997; Riel-Salvatore and Negrino, 2009; Falcucci et al., 2024a). This diversity in raw material size, quality, and sourcing is beneficial to our study as it allows us to evaluate whether raw material selection and accessibility drive significant differences between PA assemblages or if these assemblages cluster closely together despite these confounding factors, suggesting strong shared norms in lithic production.

Table 3 presents the quantification of the merged datasets used in this study. We filtered the PA datasets to match the criteria applied to Ksar Akil by including only complete blades and bladelets with less than 33% dorsal cortical coverage, along with all tools and cores. Among the three sites, Fumane provides the largest assemblage, with a substantial sample of shaped tools, notably retouched bladelets, many of which are fragmented (Falcucci et al., 2017, 2018). Cores are well represented across all sites, while core-tools are particularly characteristic of layers XIII—XIB at Ksar Akil.

3.3. Methodology

Quantitative analyses to assess technological similarities and differences between layers XIXB—XIB at Ksar Akil and the PA assemblages from Bombrini, Castelcivita, and Fumane follow the analytical framework of the reduction sequence (Conard and Adler, 1997; Andrefsky, 1998; Odell, 2004; Scerri et al., 2016). All artifacts were classified into broad technological categories. The definition of core-tools used here differs from what is commonly used for Lower Paleolithic assemblages (e.g., hand axes, cleavers, and spheroids). For this study, the class includes artifacts involved in bladelet production—such as carinated end-scrapers and burin cores—which are also often classified as tools (Demars and Laurent, 1992).

A range of continuous and discrete attributes related to different stages of the core reduction sequence were recorded. These attributes were selected based on a comprehensive body of research on laminar technologies from the IUP and EUP (e.g., Nigst, 2012; Zwyns, 2012; Falcucci et al., 2017; Tafelmaier, 2017). Linear measurements (e.g., length, width, and thickness) were taken using a digital caliper with a precision of 0.2 mm and a resolution of 0.1 mm. Blanks were measured after being oriented along their technological axis. We categorized laminar blanks into two main groups—blades and bladelets—based on the metric boundary established by Tixier (1963), which defines bladelets as laminar blanks with a width equal or less than 12 mm. Cores were measured according to a technological orientation so that length refers to the longitudinal axis of the flaking surface, following Lombao et al. (2023). In addition to linear measurements, three-dimensional (3D) volume was calculated for cores and core-tools. For this, we utilized 3D meshes from Open Access repositories associated with the PA assemblages (Falcucci and Moroni, 2025; Falcucci and Peresani, 2025; Falcucci et al., 2025b, 2025c) and newly 3D-scanned cores from Ksar Akil. The computed volumes were recorded in cubic millimeters. Cortex coverage for both cores and blanks was categorized into five ordinal intervals: 0%, 1—33%, 33—66%, 66—99%, and 100%.

This comparative analysis is grounded in the middle-range theoretical framework of the behavioral approach to cultural transmission (Tostevin, 2013, 2019). Developed to quantify social contacts through detailed lithic analyses, this method has been further refined by Scerri et al. (2014) and Cascalheira (2019) for the application of multivariate statistical techniques (see also Radinović and Dragosavac, 2025). These techniques enable robust comparative analyses between different assemblages by identifying central tendencies in lithic attributes, which are sorted into clusters that reflect specific technological decisions. This approach allows for precise quantification of similarities and differences across assemblages, shedding light on the role of shared learned behaviors and cultural backgrounds in shaping observed patterns. To facilitate this analysis, attributes were organized into heuristic categories representing various domains of core reduction procedures. Table 4 presents the categories across the various lithic domains examined, along with their corresponding variable categories and the associated abbreviations.

The analysis of blanks focused on three primary domains: platform maintenance, direction of core exploitation, and dorsal convexity management. To minimize the impact of raw material variability across regions and the incompleteness of the Ksar Akil assemblages, we prioritized technological and morphological attributes over artifact sizes. Linear measurements were used to calculate key dimensionless morphological parameters, such as elongation (length-to-width ratio) and flattening (width-to-thickness ratio). By grouping inter-related blank attributes into these domains, we were able to examine the relationships between variables commonly linked to interconnected knapping actions. This lithic domain-based approach further enables the reduction sequence to be broken down into comparable clusters, thereby mitigating potential biases related to sample selection and the completeness of reduction sequences across different sites and layers (Scerri et al., 2014; Cascalheira, 2019).

Table 3
Artifact distribution by lithic class across the studied assemblages from Ksar Akil (XIXB—XIB) and the Italian Protoaurignacian sites (Bombrini, Castelcivita, and Fumane).

Layer	Code	Blade/let	Core	Core-tool	Tool	Total
Bombrini, A2-A1	RB_A2-A1	430 (45.6%)	65 (6.9%)	7 (0.7%)	441 (46.8%)	943
Castelcivita, rsa'	CTC_rsa'	302 (47.4%)	107 (16.8%)	16 (2.5%)	212 (33.3%)	637
Fumane, A2-A1	RF_A2-A1	881 (22.2%)	137 (3.5%)	24 (0.6%)	2918 (73.7%)	3960
Ksar Akil, XIB	KA_XIB	181 (29.1%)	73 (11.7%)	155 (24.9%)	213 (34.2%)	622
Ksar Akil, XIII-XII	KA_XIII-XII	226 (43.4%)	66 (12.7%)	81 (15.5%)	148 (28.4%)	521
Ksar Akil, XVI	KA_XVI	433 (42.1%)	138 (13.4%)	10 (1.0%)	447 (43.5%)	1028
Ksar Akil, XVII	KA_XVII	231 (50.3%)	74 (16.1%)	10 (2.2%)	144 (31.4%)	459
Ksar Akil, XVIII	KA_XVIII	118 (35.4%)	59 (17.7%)	7 (2.1%)	149 (44.7%)	333
Ksar Akil, XIXA	KA_XIXA	292 (36.7%)	166 (20.9%)	25 (3.1%)	313 (39.3%)	796
Ksar Akil, XIXB	KA_XIXB	212 (46.2%)	41 (8.9%)	6 (1.3%)	200 (43.6%)	459
Total		3306 (33.9%)	926 (9.5%)	341 (3.5%)	5185 (53.1%)	9758

Percentages are provided in brackets. The second column lists the abbreviation code for each assemblage, referenced in subsequent analyses.

Table 4
Overview of the attribute sets studied across the different lithic domains, including their variable categories and corresponding abbreviations (Abbr.).

Attribute	Abbr.	Variable category and abbreviations
Platform maintenance		
Bulb type	BUL	Absent = Abs, Moderate = Mod, Pronounced = Pro
Elongation	ELO	Low/High
Lip type	LIP	Absent = Abs, Moderate = Mod, Pronounced = Pro
Platform type	PLT	Facetted = Fac, Linear = Lin, Plain = Pla, Punctiform = Punct, Other = Oth
Platform shape	PLS	Linear = Lin, Oval = Ova, Punctiform = Punct, Rectangular = Rect, Triangular = Tri, Other = Oth
Direction of core exploitation		
Length	LEN	Supplementary quantitative variable
Scars number	SCN	0, 1, 2, 3+
Scar pattern	SCP	Bidirectional = Bid, Unidirectional subparallel = UniP, Unidirectional convergent = UniC, Other = Oth
Dorsal surface convexity		
Blank shape	BLS	Convergent = Conv, Irregular = Irreg, Subparallel = SubP, Other = Oth
Curvature, profile	CURV	Straight = Str, Curved slightly = CurvS, Curved = Curv, Curved intense = CurvI
Distal end shape	DIST	Convex = Cx, Irregular = Irreg, Pointed = Point, Straight = Str
Elongation	ELO	Low/High
Flattening	FLAT	Low/High
Twisting, profile	TWIST	Nontwisted = TwN, Twisted = TwY
Laminar cores		
Elongation	ELO	Low, Medium, and High
Flaking surface	FLS	Bidirectional = Bid, Unidirectional = Uni
Flattening	FLAT	Low, Medium, and High
Platform number	PLAT	1 = 1, 2-opposed = 2-Opp, 2-unrelated = 2-Unr, 3
Reduction pattern	REDP	Convergent = Conv, Subparallel = SubP
Blank selection and retouching		
Blank shape	BLS	Convergent = Conv, Irregular = Irreg, Subparallel = SubP, Other = Oth
Cortex	CORT	0%, 1−33%, >33%
Curvature, profile	CURV	Straight = Str, Curved slightly = CurvSl, Curved = Curv
Distal end	DIST	Convex = Cx, Irregular = Irreg, Pointed = Point, Straight = Str
Elongation	ELO	Low/High
Flattening	FLAT	Low/High
Retouch position	RETP	Alternate = Alt, Direct = Dir, Inverse = Inv
Twisting, profile	TWIST	Non-twisted = TwN, Twisted = TwY

The platform domain focuses on the maintenance of the core's striking platforms and the application of different striking gestures (Dibble, 1997). Relevant attributes include platform type, platform shape, the presence and development of lips and bulbs, and blank elongation. Elongation was used as a proxy for the external platform angle, which was excluded due to known interobserver biases in measuring this attribute (Cochrane, 2003; Li et al., 2022). Studies have demonstrated a significant correlation between external platform angle and elongation (Dibble and Rezek, 2009), supporting the validity of elongation as a substitute for striking angle variability. The direction of core exploitation domain quantifies core exploitation through scar pattern directionality and the number of dorsal scars. Scar pattern direction reflects the core rotation strategy, while the number of dorsal scars indicates the selection and use of guiding ridges during blank removal. The dorsal convexity domain examines how convexities were maintained during the reduction sequence to produce target blanks. Attributes recorded on laminar blanks to assess this domain included elongation, flattening, profile curvature, profile twisting, cross-section shape, blank outline shape, and distal-end shape.

The core analysis aimed to understand the technological systems underlying raw material exploitation at the studied sites. Only nonshattered cores with blade and/or bladelet negatives were included. Attributes considered in this analysis include elongation, flattening, knapping direction (e.g., unidirectional or bidirectional), reduction pattern (i.e., scar orientation on the flaking surface), and the number and configuration of striking platforms. Morphological data, such as elongation and flattening, are influenced by the orientation of the striking platforms and flaking surfaces, as well as the degree of core reduction (Clarkson, 2013; Blinkhorn et al., 2021; Lombao et al., 2023). These attributes provide essential information to complement the blank analysis, which is particularly important given the sample bias in the Ksar Akil assemblage.

Finally, we explored blank selection and modification by analyzing all recovered tools. Tool types were classified using a revised and simplified version of common typologies (de Sonneville-Bordes, 1960; Demars and Laurent, 1992), as outlined in Falcucci et al. (2024a). We further analyzed blank selection and the variability of laterally modified tools in terms of retouch position, morphological features, and cortex coverage. This analysis focused on laminar tools typically classified as Dufour subtype Dufour bladelets and Krems, Font-Yves, El-Wad, and Ksar Akil point types, which are represented in both PA and Ahmarian assemblages (Goring-Morris and Belfer-Cohen, 2003; Le Brun-Ricalens et al., 2009; Tsanova et al., 2012; Kadowaki et al., 2015; Falcucci et al., 2018).

All attributes were first quantified and visualized using tables and stacked bar charts created using the R (Posit team, 2023; R Core team, 2023) package *ggstatsplot* (Patil, 2021). We then performed multiple correspondence analyses (MCAs) using the *FactoMineR* and *factoextra* packages (Lê et al., 2008; Kassambara and Mundt, 2017), utilizing the Burt matrix method to explore interactions among categorical variables within the heuristic domains described above. The MCA, an extension of correspondence analysis, allows for the investigation of relationships among multiple categorical variables (Abdi and Valentin, 2007). In the analysis, the site and layer of provenience were used as supplementary qualitative variables, while lithic attributes were used as active categorical variables. The number of MCA dimensions retained was set to 15, balancing sufficient explanation of variance while minimizing overfitting. Continuous variables, such as elongation and flattening, were transformed into categorical

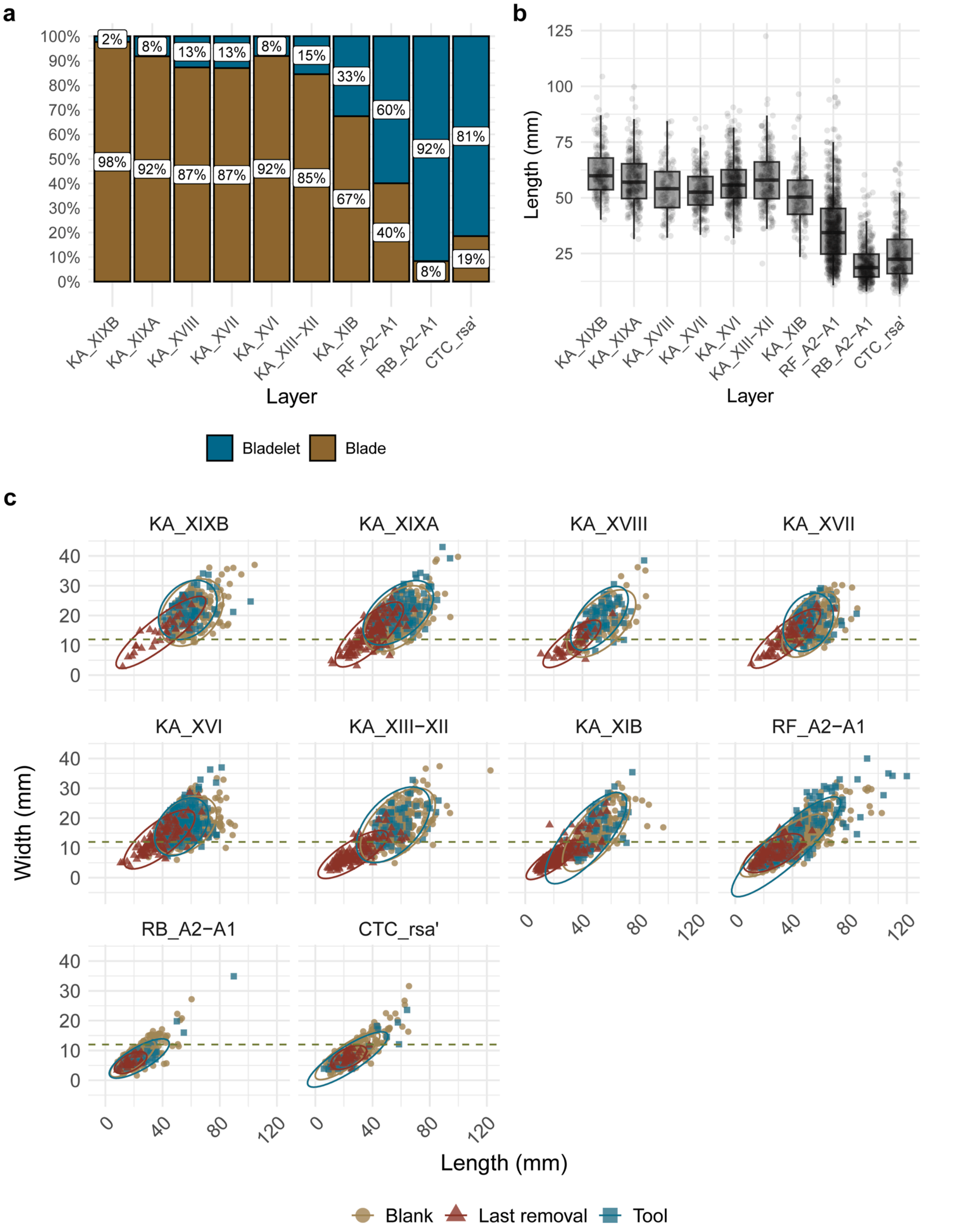

Figure 3. Metric analysis of the Ksar Akil and Protoaurignacian assemblages. **a.** Percentage distribution of blades and bladelets among nonretouched blanks. **b.** Boxplots with jittered points showing the length values (in mm) of nonretouched laminar blanks (blades and bladelets). **c.** Scatterplots illustrating the distribution of length and width (in mm) values for both retouched (i.e., tool) and nonretouched (i.e., blank) laminar blanks (blades and bladelets), as well as the last laminar removal (i.e., last removal) measured on blade and bladelet cores. A green dashed line indicates the 12-mm width limit used for sorting blades from bladelets. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

variables by binning the data. Blanks were divided into two categories (i.e., low and high values), while cores were split into three (i.e., low, medium, and high), based on ‘natural’ breaks in their distributions using the *RcmdrMisc::binVariable()* function. This function determines cut-points using *k*-means clustering, which groups values in a way that minimizes within-group variance. To ensure comparability across assemblages, thresholds were calculated globally rather than separately for each group. SOM Tables report the break values used for binning, along with summary statistics (i.e, mean, median, and SD) for elongation and flattening by assemblage and bin, clarifying how these categories structure variation within each group. Finally, to further reduce noise, categories with less than 5% representation were lumped into an ‘other’ category using the *forcats::fct_lump()* function, ensuring the analysis focused on dominant patterns in the data.

Given the large number of subsamples in the dataset, we did not perform pairwise statistical tests, or nonparametric multivariate analyses of variance, to avoid issues with overfitting and repeated measures. Instead, we used distance matrices and clustering techniques to uncover underlying relationships among groups. The MCA-generated coordinates were used to calculate the centroid (central tendency) for each group (site and layer). A Euclidean distance matrix between these centroids was then computed to measure dissimilarity between groups, with results visualized in a heatmap. To further analyze the structure of the data, hierarchical clustering was applied to the centroid distance matrix using the *hclust()* function with the Ward method (Kaufman and Rousseeuw, 1990). This method constructs a dendrogram representing pairwise distances between clusters. The optimal number of clusters was determined using the silhouette method (Rousseeuw, 1987), which evaluates clustering quality based on both cohesion (how similar elements within a cluster are) and separation (how distinct clusters are from one another). A silhouette plot was used to identify the cluster configuration with the highest average silhouette width, indicating the most suitable clustering solution. The final clustering results were visualized through a dendrogram. Finally, we performed multidimensional scaling (MDS)—also known as principal coordinate analysis—on the distance matrix to visualize the pairwise relationships between groups in a lower-dimensional space (Cox and Cox, 2000). This visualization preserved the pairwise distances and highlighted underlying patterns of variability in the dataset.

4. Results

4.1. Preliminary exploration of the dataset

While blades are the most common laminar blanks throughout the Ksar Akil sequence, the PA assemblages are overwhelmingly dominated by bladelets. The percentage of nonmodified bladelets ranges from 57% at Fumane to approximately 91% at Bombrini (Fig. 3a and SOM Table S11). This prevalence of small-sized blanks, often modified into Dufour tools, is typical for the PA (Bon and Bodu, 2002; Falcucci et al., 2018). In our sample from Ksar Akil, the highest proportion of bladelets is observed in layer XIB, although the bladelet category is under-represented across the sequence as a whole (see SOM Note 1). The scarcity of bladelets in the lower layers at Ksar Akil is evident when cores are sorted by the type of laminar scars visible at discard (i.e., blades, bladelets, or both; SOM Fig. S6). While bladelet scars are observed on cores throughout the sequence, they are less common in layers XIXB–XVI and become prominent only in layers XIII–XIB, where cores with only blade scars are rare. In the PA assemblages from Castelcivita and Bombrini, no cores with only blade scars were recorded. At Fumane, the percentage of bladelet scars on cores aligns closely with that of layers XIII–XIB at Ksar Akil.

These findings suggest that in the lower layers at Ksar Akil, toolmakers produced bladelets less frequently than did people occupying the upper layers XIII–XIB and the PA sites. Blanks in the PA assemblages are significantly smaller than those at Ksar Akil, as shown by the length distributions in Figure 3b. This difference is further illustrated in scatterplots in Figure 3c, which display length and width values with 95% confidence ellipses, grouped by blanks, tools, and the last laminar negatives on cores. In the PA datasets, the lengths and widths of the smallest tools, blanks, and cores' last negatives overlap extensively, indicating the effects of core reduction intensity at all three sites. This stands in contrast to the Ksar Akil assemblages, where nonrecovery of small blanks resulted in much less overlap between negatives on cores and actual artifacts in the deposit. However, the degree of overlap varies across the Ksar Akil sequence, with the most pronounced differences occurring in the upper layers.

To account for the effects of biased sampling in the subsequent MCA analyses, we subset the PA blank datasets based on length values. An artificial cutoff of 25 mm—corresponding to the size below which laminar blanks were in most cases not collected at Ksar Akil (Frahm and Tryon, 2019)—will be applied. Importantly, no size threshold was imposed when analyzing complete bladelets from the PA datasets. This cutoff primarily affects the Bombrini and Castelcivita datasets, which are characterized by the use of small nodules and, at Bombrini, increased reliance on exogenous raw materials. Splitting the PA blank datasets into two groups, labeled ‘small’ and ‘large’ based on size, will allow us to explore the impact of size bias on other technological and morphological attributes. For clarity, the PA datasets will be renamed accordingly (e.g., RF_small and RF_large).

4.2. Blank analysis

Platform maintenance The attributes related to platform maintenance are summarized in SOM Tables S12–S17 and SOM Figures S7–S11. These data reveal significant variability across the studied assemblages. The scree plot of the MCA shows that the first three dimensions account for 64.4% of the total variance (SOM Fig. S12), with subsequent dimensions contributing substantially less. Platform type and shape emerge as the primary contributors to the first two dimensions (SOM Fig. S13). Variables related to bulbs and lips strongly influence dimension 1, while elongation plays a minor role. The contribution of various variable categories to these dimensions is visualized in SOM Figures S14–S15. Linear platforms contribute significantly to dimension 1, followed by categories such as absent or moderately developed lips, faceted platforms, absent bulbs, and punctiform platforms. Conversely, punctiform platforms are strongly correlated with dimension 2.

The relationships between these variable categories are further illustrated in Figure 4a. Platform types and shapes—particularly linear and punctiform platforms—are closely inter-related. Blanks without bulbs and with moderately developed lips are associated with positive scores on dimension 1, while faceted platforms, pronounced bulbs, and absent lips occupy the negative scores. Other categories, such as plain platforms, pronounced lips, and moderately developed bulbs, contribute less and are positioned near the plot's center.

When data points are plotted by site and layer, distinct patterns emerge. The Ksar Akil assemblages exhibit a clear diachronic trend along dimension 1, with lower layers (XIXB–XVIII) clustering in the negative scores and upper layers (XVI–XIB) moving toward the plot's center (SOM Fig. S16). Layers XIXB–XVIII appear well

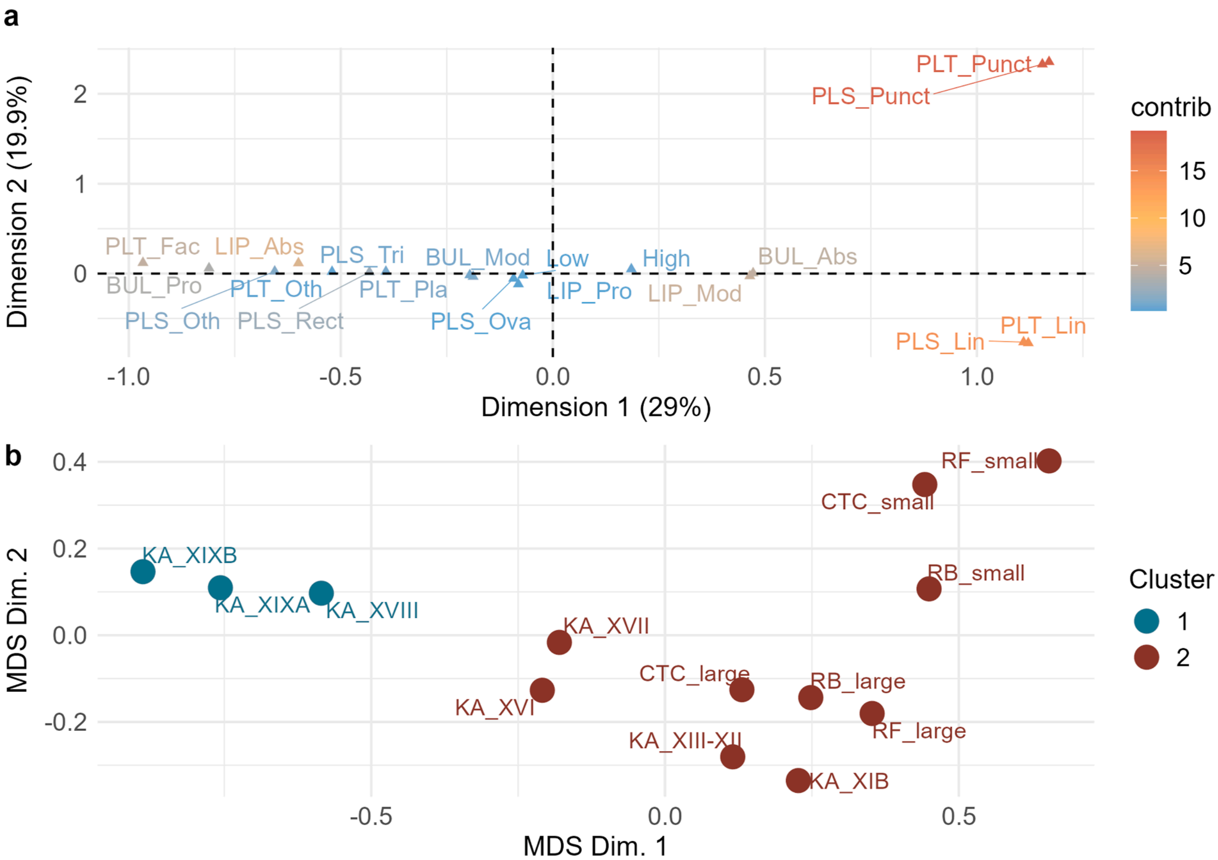

Figure 4. Platform maintenance analysis. **a.** Multiple correspondence analysis (MCA) plot displaying the contribution of the variable categories to the definition of the first and second dimensions. The color gradient (see the legend for color coding) represents the percentage of the contribution. **b.** Multidimensional scaling (MDS) plot showing the spatial relationships between the identified clusters, which are color coded. Please note that the spatial arrangement of the assemblages in the MDS plot does not directly correspond to the MCA plot in panel **a** as the MDS is based on the pairwise distances between assemblages, whereas the MCA plot is based on the dimensional reduction of categorical variables. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

distinct from layers XVII—XVI in terms of platform attributes. The PA assemblages display clustering behavior influenced by size-based sorting. Blanks shorter than 25 mm are positioned further from the main groups, while blanks longer than 25 mm cluster near the upper Ksar Akil layers XIII—XIB.

These observations are confirmed by the distance matrix (SOM Fig. S17), while hierarchical clustering analysis identifies two primary groups (SOM Figs. S18—S19). The first group consists of blanks from Ksar Akil layers XIXB—XVIII, often characterized by faceted platforms and pronounced bulbs. The second group includes all other assemblages, characterized by blanks with moderately developed or absent bulbs and the presence of lips, indicating a clear shift from hard hammer percussion to soft hammer percussion (see Fig. 5). Within this second group, further subdivisions are noted, particularly based on lip formation and platform thickness. These differences are most pronounced in the small-sized PA blanks. The MDS plot highlights the distinct positioning of small PA blanks while showing the marked separation between the two primary clusters (Fig. 4b).

Direction of core exploitation The attributes related to the direction of core exploitation are summarized in SOM Tables S18—S19 and SOM Figures S20—S21. The MCA scree plot indicates that the first four dimensions account for 75.8% of the variance in the dataset (SOM Fig. S22). Both dorsal scar pattern and the number of dorsal scars contribute significantly to the first two dimensions (SOM Fig. S23). Dimension 1 is primarily influenced by blanks with 1 or 3+ dorsal scars, as well as by 'other' and unidirectional convergent scar patterns (SOM Fig. S24). In dimension 2, the key contributors are bidirectional and 'other' scar patterns, along with the presence of 2 or 3+ dorsal scars (SOM Fig. S25).

The relationships between variable categories are visualized in Figure 6a. Strong correlations are observed between bidirectional scar patterns and blanks with 3+ dorsal scars, as well as between unidirectional convergent scar patterns and blanks with 2 dorsal scars. There is a slightly weaker correlation between unidirectional subparallel scar patterns and blanks with 1 dorsal scar. The 'other' scar pattern category plots at the extreme positive end of dimension 1, opposite to the bidirectional scar pattern.

When sorted by site and layer, some distinct patterns emerge. Layers XVI and XVII at Ksar Akil plot toward the negative axis of dimension 1, driven by the high prevalence of bidirectional dorsal scars (SOM Fig. S26). However, unlike the platform analysis, no clear diachronic trend is evident due to the alternating importance of unidirectional and bidirectional scar patterns across the layers studied. Layers XIII—XII and XIB plot closest to the Fumane blanks larger than 25 mm, whereas the larger blanks from Bombrini and Castelcivita are the only ones positioned in the positive quadrant of both dimensions 1 and 2.

To explore whether reduction intensity contributes to the observed patterns (Tostevin, 2013), blank length was included as a supplementary quantitative variable in the MCA. The length vector showed a weak correlation with both dimension 1 ($r = -0.16$) and dimension 2 ($r = 0.14$), indicating only a limited association between blank size and specific dorsal scar configurations or scar

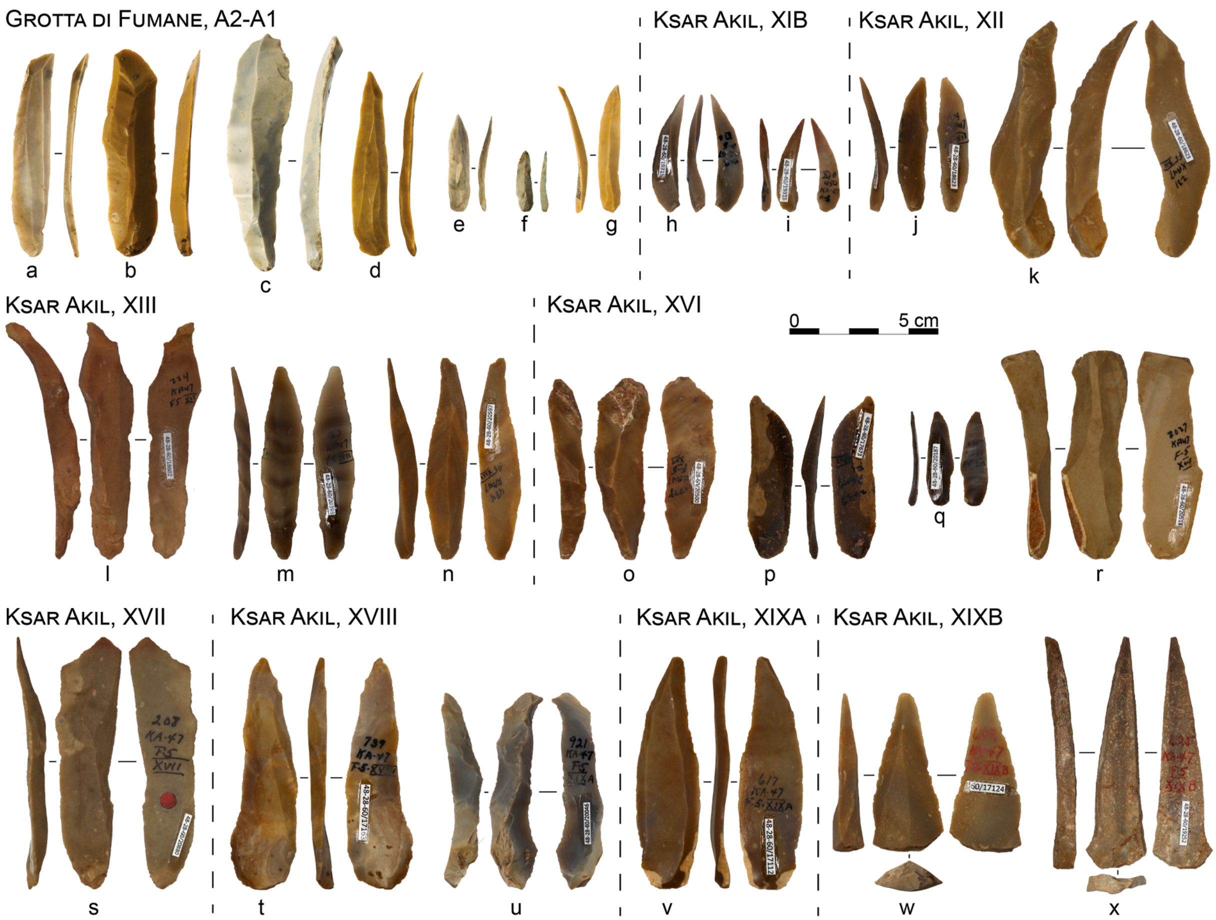

Figure 5. Example of unmodified blades and bladelets from Grotta di Fumane (**a**–**g**) and the Ksar Akil sequence (**h**–**x**), sorted by site and layer of provenience. a, d–g, q = bladelets; b–c, p = blades; h–j = twisted bladelets; k–l, o = Neocrested blades; m–n = slightly twisted blades; r = a maintenance plunging blade; s = a blade with slight partial retouch; t, v–x = blades with faceted platforms; u = a crested blade. Fumane blanks are modified after Falcucci et al. (2017). A list of the photographed Ksar Akil blanks, along with their respective IDs, is available in the Zenodo research compendium *data* folder (Falcucci and Kuhn, 2025). Image by Armando Falcucci. Photos h–x courtesy of the Peabody Museum of Archaeology and Ethnology, Harvard University (48-28-60/19315, 48-28-60/18623, 48-28-60/18602, 48-28-60/20393, 48-28-60/20597, 48-28-60/20500, 48-28-60/17673, 48-28-60/20187, 48-28-60/20518, 48-28-60/20880, 48-28-60/17163, 48-28-60/20046, 48-28-60/17112, 48-28-60/17124, 48-28-60/19252). Permission granted for use in this publication only; any reuse requires Peabody Museum approval.

counts (SOM Figs. S23 and S27). Despite this modest correlation, potential changes in core rotation during reduction were further investigated by grouping the data by layer and, within each layer, dividing blank lengths into three equally sized classes (tertiles) using the *dplyr::ntile()* function. These were labeled as small, medium, and large. SOM Figure S28 visualizes the distribution of scar patterns among these three groups across Ksar Akil layers XIXB, XIXA, XVIII, XVII, and XVI, where bidirectional scar patterns are most frequent. A slight tendency for longer blanks to exhibit bidirectional scar patterns more often was observed, suggesting a possible shift in rotational strategies during reduction. However, this pattern is not consistent across all compared layers, and chi-squared tests of independence indicate a statistically significant association between dorsal scar pattern and length class in layer XVI only ($\chi^2 = 20.056$, $df = 6$, $p < 0.01$).

The distance matrix plot and hierarchical clustering analysis support these observations, dividing the assemblages into four clusters (SOM Figs. S29–S31). The strongest cluster division separates layers XVIII–XVI at Ksar Akil from all other assemblages, indicating a significant shift in core directional exploitation within these layers commonly attributed to the northern Ahmarian. Additionally, while all PA blanks smaller than 25 mm form a single cluster, the larger PA blanks are divided into two groups: one containing Bombrini and Castelcivita and the other grouping Fumane with Ksar Akil layers from both the lowermost sequence (XIXA–XIXB) and the upper layers (XIII–XIB). The MDS plot visualizes these findings, illustrating the clustering structure and differences between assemblages based on core exploitation patterns (Fig. 6b).

Dorsal surface convexity The quantification of attributes related to dorsal surface convexity, as assessed through the study of laminar blanks, is summarized in SOM Tables S20–S27 and SOM Figures S32–S37. The MCA scree plot shows that the first three dimensions account for 48.1% of the total variance (SOM Fig. S38), with the remaining dimensions explaining a greater proportion of the variation than the MCA on platform maintenance. Dimension 1 is strongly influenced by blank shape and distal-end shape, with profile curvature contributing to a lesser extent. While these variables also affect dimension 2, profile twisting, elongation, and flattening contribute most strongly to it (SOM Fig. S39).

The contributions of variable categories to dimensions 1 and 2 are shown in SOM Figures S40–S41. Dimension 1 is characterized by blanks with converging edges, pointed or straight distal ends, and intense profile curvatures. Dimension 2 is influenced by blanks with twisted profiles, convex or pointed distal ends, and low flattening values. Notably, blanks with low flattening, non-twisted profiles, and straight to slightly curved profiles plot in the negative axes of both dimensions (Fig. 7a).

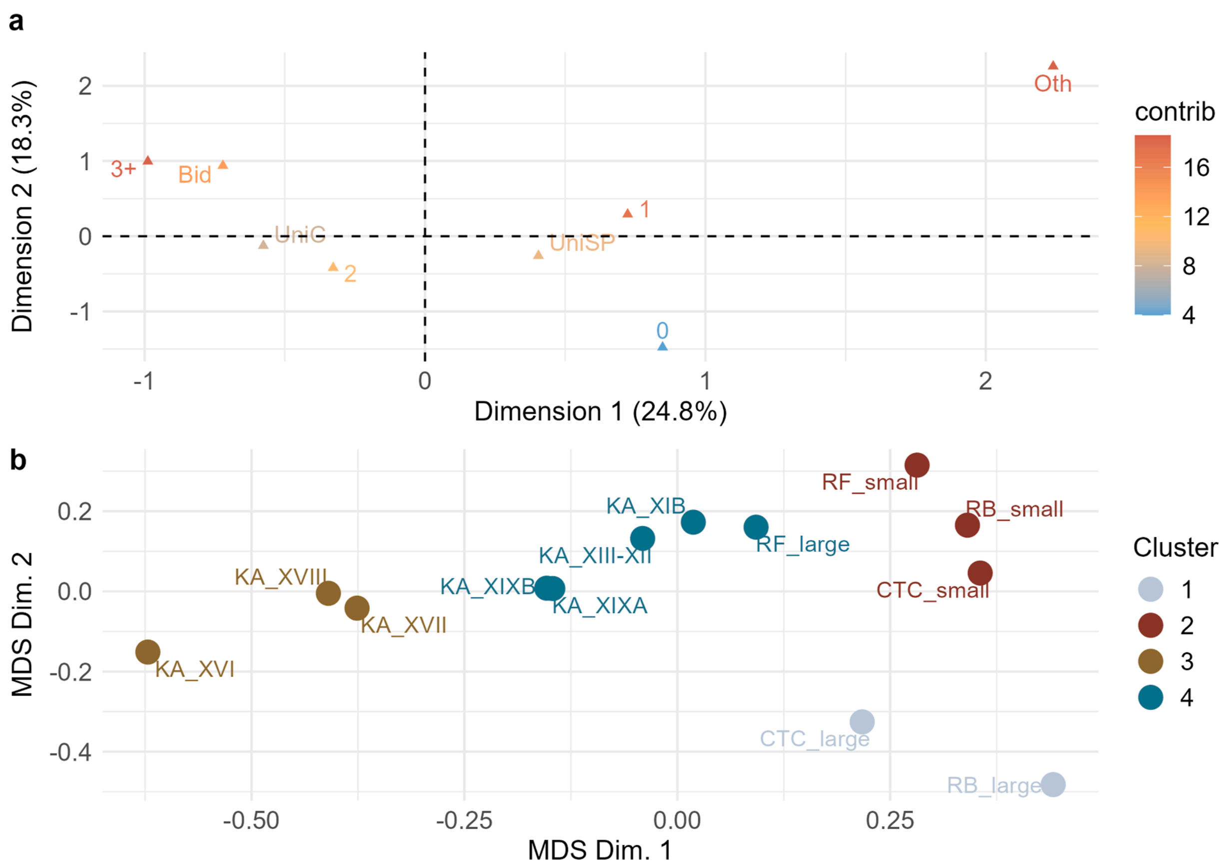

Figure 6. Direction of core exploitation analysis. **a.** Multiple correspondence analysis (MCA) plot displaying the contribution of the variable categories to the definition of the first and second dimensions. The color gradient (see the legend for color coding) represents the percentage of the contribution. **b.** Multidimensional scaling (MDS) plot showing the spatial relationships between the identified clusters, which are color coded. Please note that the spatial arrangement of the assemblages in the MDS plot does not directly correspond to the MCA plot in panel **a** as the MDS is based on the pairwise distances between assemblages, whereas the MCA plot is based on the dimensional reduction of categorical variables. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

As shown in the biplot in SOM Figure S42, this region corresponds to the centroids of the PA blanks smaller than 25 mm, as well as the Fumane blanks larger than 25 mm. These groups display a marked separation from all other assemblages. Most other groups cluster closer to the plot's center, with the exception of layers XIII–XIB at Ksar Akil, which are more separated due to the presence of numerous blanks with twisted profiles (see Fig. 5 and SOM Fig. S33).

The distance matrix plot confirms these patterns (SOM Fig. S43), while the hierarchical clustering analysis divides the assemblages into four clusters (SOM Figs. S44–S45). The strongest separation is observed between the Ksar Akil assemblages and all other PA assemblages, except for the Bombrini blanks larger than 25 mm. The separation of Bombrini from the other PA sites is largely driven by the higher frequency of maintenance blades with twisted profiles in that assemblage. The MDS plot further illustrates these findings, showing a clear separation between the identified clusters (Fig. 7b).

4.3. Laminar core analysis

The core analysis holds significant relevance in this study because there is strong confidence that all laminar cores from Ksar Akil were recovered and stored, making this artifact class less susceptible to selective discarding (Fig. 8). The analyzed laminar cores display marked variation in volume. Figure 9 presents the distribution of core volumes across the studied assemblages following a logarithmic transformation. This transformation was applied to address the strong skewness in the raw data as core volumes span a wide range and include a few disproportionately large specimens. An analysis of variance reveals a significant difference in the logarithmically transformed volume values ($F = 52.37$, $p < 0.01$), indicating substantial differences between assemblages. A Tukey honest significant difference post hoc test, conducted following the analysis of variance, shows that 29 out of 45 pairwise comparisons are statistically significant (SOM Table S28). SOM Figure S46 visualizes these comparisons, showing, for instance, that the Fumane cores differ significantly from the other PA assemblages, likely due to inter-regional differences in raw material size and availability, as discussed in Section 3.2. Within the Ksar Akil assemblages, volume differences are generally more pronounced when comparing upper and lower layers, particularly with regard to layer XIB. One notable exception is layer XVIII, where lower core volume values may reflect differences in reduction intensity. This pattern warrants further investigation in future site-based studies.

SOM Tables S29–S35 and SOM Figures S47–S51 summarize the attributes used in the MCA and highlight notable differences. The MCA scree plot shows that the first dimension explains approximately 43% of the variance, with subsequent dimensions contributing significantly less (SOM Fig. S52). Direction of flaking and the number of striking platforms are the primary contributors to dimension 1, while reduction pattern and core flattening play

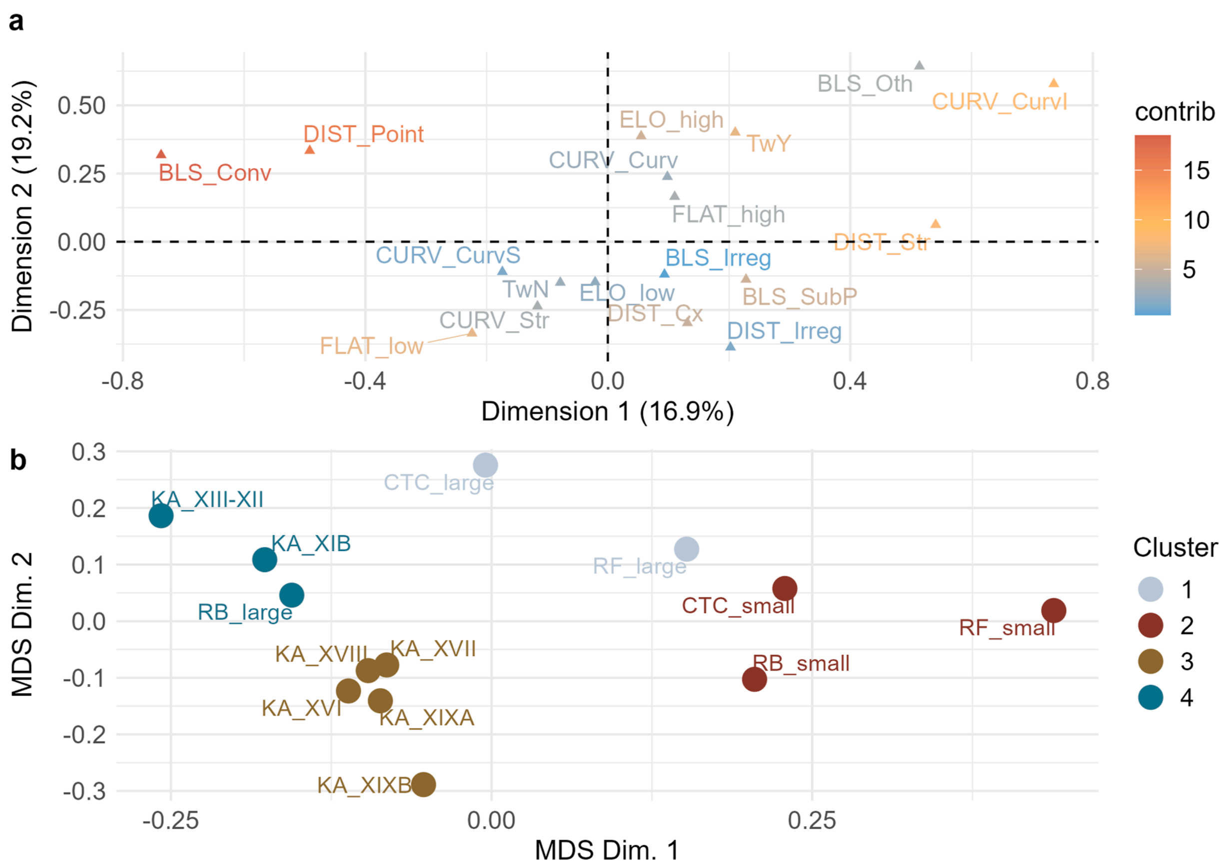

Figure 7. Dorsal surface convexity analysis. **a.** Multiple correspondence analysis (MCA) plot displaying the contribution of the variable categories to the definition of the first and second dimensions. The color gradient (see the legend for color coding) represents the percentage of the contribution. **b.** Multidimensional scaling (MDS) plot showing the spatial relationships between the identified clusters, which are color coded. Please note that the spatial arrangement of the assemblages in the MDS plot does not directly correspond to the MCA plot in panel **a** as the MDS is based on the pairwise distances between assemblages, whereas the MCA plot is based on the dimensional reduction of categorical variables. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

lesser roles (SOM Fig. S53). In contrast, dimension 2 is strongly influenced by morphological variables, specifically core elongation and flattening.

SOM Figure S54 shows that bidirectional flaking and opposed striking platforms have the highest influence on dimension 1. Unidirectional flaking and single striking platforms also contribute but to a lesser extent. Dimension 2 is predominantly influenced by core elongation and flattening categories (SOM Fig. S55). Relationships between these variable categories are visualized in Figure 10a, indicating strong correlations between bidirectional cores and two opposed striking platforms, as well as between single platforms and unidirectional convergent reduction patterns. High elongation values are inversely correlated with core flattening values, reflecting expected morphological trade-offs.

When sorted by site and layer, the centroid values indicate significant differences between groups. Cores from the lower layers at Ksar Akil, except for layer XIXA, plot far from other groups (SOM Fig. S56). PA cores cluster closely together, while the upper layers XIII–XIB at Ksar Akil form a distinct and coherent group with no overlap with other assemblages. These differences are primarily influenced by two core technologies: the bidirectional prismatic cores characteristic of the Ahmarian layers and the high frequency of burin cores (e.g., carinated burins and multiple burins) in layers XIII–XIB.

The distance matrix plot (SOM Fig. S57) and hierarchical clustering analysis corroborate these findings, dividing the assemblages into three clusters (SOM Figs. S58–S59). An interesting result is the clustering of layer XIXB with the PA cores, mostly driven by the increased use of unidirectional flaking on platform cores. This further highlights internal variability within the layers typically attributed to the Ahmarian. The MDS plot illustrates these observations, emphasizing the clear distinctions between groups, particularly the technological differences observed in layers XIII–XIB (Fig. 10b).

4.4. Tool analysis

General overview A substantial number of retouched tools were recovered from the studied assemblages. SOM Table S36 provides a comprehensive list of tools, based on the minimum number of flaked products (i.e., all mesial and distal fragments excluded from the count). The PA assemblages are characterized by a high frequency of retouched bladelets, which are under-represented in the Ksar Akil datasets, probably due to the previously described recovery biases. In contrast, layers XIII–XIB at Ksar Akil are notable for a high frequency of multiple and carinated burins, which are uncommon in the other assemblages. Figure 11 classifies all tools—except retouched bladelets—based on the minimum number of flaked products, grouping them into broad categories to highlight key differences. The lower layers at Ksar Akil are primarily dominated by laterally retouched tools and endscrapers. There is a sharp increase in the importance of burins in layers XIII–XII and XIB. In contrast, the PA assemblages are predominantly characterized by laterally retouched tools, which remain

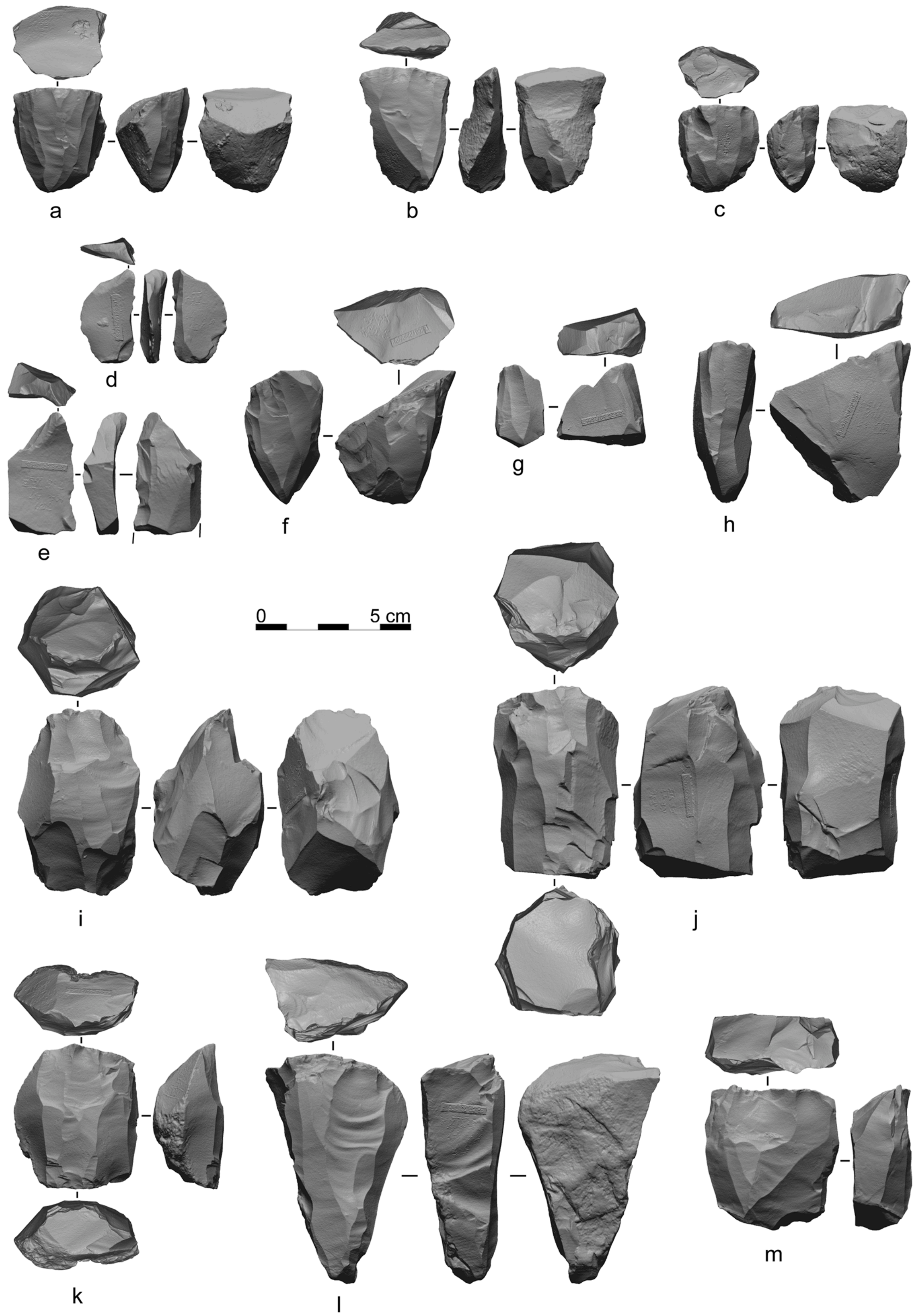

Figure 8. Examples of laminar cores analyzed at Ksar Akil (**d**–**m**) and the Italian Protoaurignacian sites (**a**–**c**). a–c and f are semicircumferential bladelet cores; d–e are carinated burin bladelet cores; g and h are narrow-sided (burin-like) bladelet cores; i–k are bidirectional blade cores; l–m are unidirectional blade cores. Stratigraphic origin: Ksar Akil, layers XIXB (m), XIXA (l), XVII (k), XVI (i, j), XIII (h), XII (f, g), XIB (d, e); Grotta di Fumane, layer A2 (a); Riparo Bombrini, layer A1 (b); Grotta di Castelcivita, layer rsa' (c). The 3D views were created using the *Create Plate* function in Artifact3-D (Grosman et al., 2022). The Protoaurignacian 3D models are part of the Open Aurignacian Project (Falcucci et al., 2025c) and can be downloaded from the open-access repositories of Grotta di Castelcivita (Falcucci and Moroni, 2025), Grotta di Fumane (Falcucci and Peresani, 2025), and Riparo Bombrini (Falcucci et al., 2025b). A list of the cores with their respective IDs can be found in the Zenodo research compendium *data* folder (Falcucci and Kuhn, 2025). Image by Armando Falcucci. Images d–m courtesy of the Peabody Museum of Archaeology and Ethnology, Harvard University (48-28-60/18979, 48-28-60/19320, 48-28-60/18068, 48-28-60/18053, 48-28-60/20915, 48-28-60/19620, 48-28-60/21348, 48-28-60/17634, 48-28-60/20543). Permission granted for use in this publication only; any reuse requires Peabody Museum approval. 3D = three dimensional.

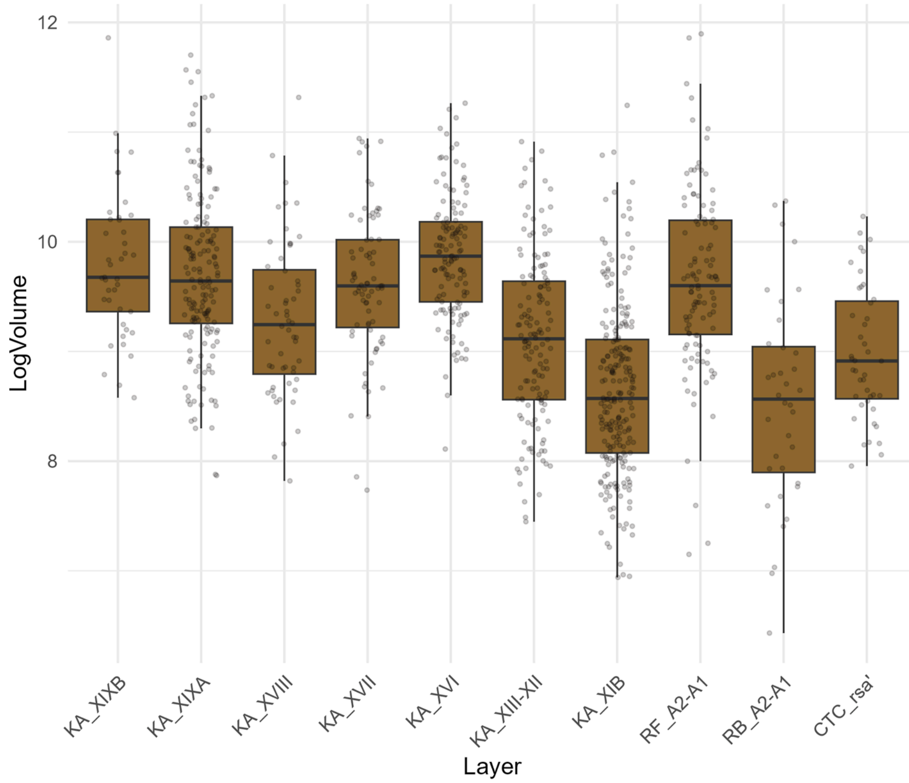

Figure 9. Boxplots with jittered points of logarithmically transformed volume values (LogVolume) for cores with laminar negatives across the Ksar Akil and Protoaurignacian assemblages. The logarithmic transformation was applied to address the strong skewness in the raw data as core volumes span a wide range and include a few disproportionately large specimens.

the most significant category across Fumane, Bombrini, and Castelcivita.

Multiple correspondence analysis of laterally modified tools This analysis included all tools with lateral or convergent retouch from Ksar Akil and Fumane (Fig. 12). The two groups were merged into a single category as the only difference between them is whether the retouch extends toward the distal tip of the blank. Retouched tools from Bombrini and Castelcivita were excluded from this MCA due to insufficient sample sizes (Bombrini: below 25 mm, $n = 20$; above 25 mm, $n = 16$; Castelcivita: below 25 mm, $n = 18$; above 25 mm, $n = 11$), which would limit meaningful comparisons. The attributes used in the analysis are summarized in SOM Tables S37–S46 and SOM Figs. S60–S67. The MCA scree plot shows that the first four dimensions account for 49% of the total variance (Fig. S68). The variable plot indicates that both blank shape and distal-end shape significantly influence dimensions 1 and 2 (SOM Fig. S69). Elongation and cortex coverage have a moderate influence on dimension 1, while profile twisting and retouch position contribute almost exclusively to dimension 2. Curvature and flattening, on the other hand, play a minor role overall.

The contributions of variable categories to dimensions 1 and 2 are presented in SOM Figures S70–S71. Dimension 1 is strongly influenced by tools with converging or subparallel edges, pointed or convex distal ends, and both high and low elongation scores. Dimension 2 is primarily influenced by tools with alternate retouch, twisted profiles, irregular distal ends, and 'other' blank shapes. The MCA biplot in Figure 13a illustrates how these variable configurations are distributed. Tools with converging shapes dominate the negative axis of dimension 1, while tools with subparallel shapes and convex or straight distal ends occupy the positive axis. Interestingly, twisted profiles plot on the negative axis of dimension 2, directly opposite to the alternate retouch category.

The MCA individual biplot reveals that tools from Fumane, regardless of size, consistently have negative scores on dimension 1 and positive scores on dimension 2 (SOM Fig. S72). This positioning separates them clearly from the tools at Ksar Akil. Among the Ksar Akil assemblages, tools from layer XIB stand out, showing the most distinct scores along dimension 1 while displaying similar values to layer XIII–XIB on dimension 2, particularly in terms of profile twisting.

The distance matrix plot (SOM Fig. S73) and hierarchical clustering analysis (SOM Figs. S74–S75) identify three main groups within the sample. The PA tools from Fumane form a distinct, independent cluster. The Ksar Akil tools are divided into two clusters: one comprising the upper layers (XIII–XIB) and another encompassing the lower layers (XIXB–XVI). These divisions are further visualized in the MDS plot in Figure 13b, which simplifies the relationships between groups into a two-dimensional space, clearly illustrating the separation between the clusters.

5. Discussion

5.1. Summarizing the technological differences and similarities between the Protoaurignacian and the lithic assemblages from Ksar Akil

Table 5 summarizes results from comparisons of sets of technological attributes across PA and Ksar Akil assemblages. Groups of assemblages were considered to 'cluster with' each other (first

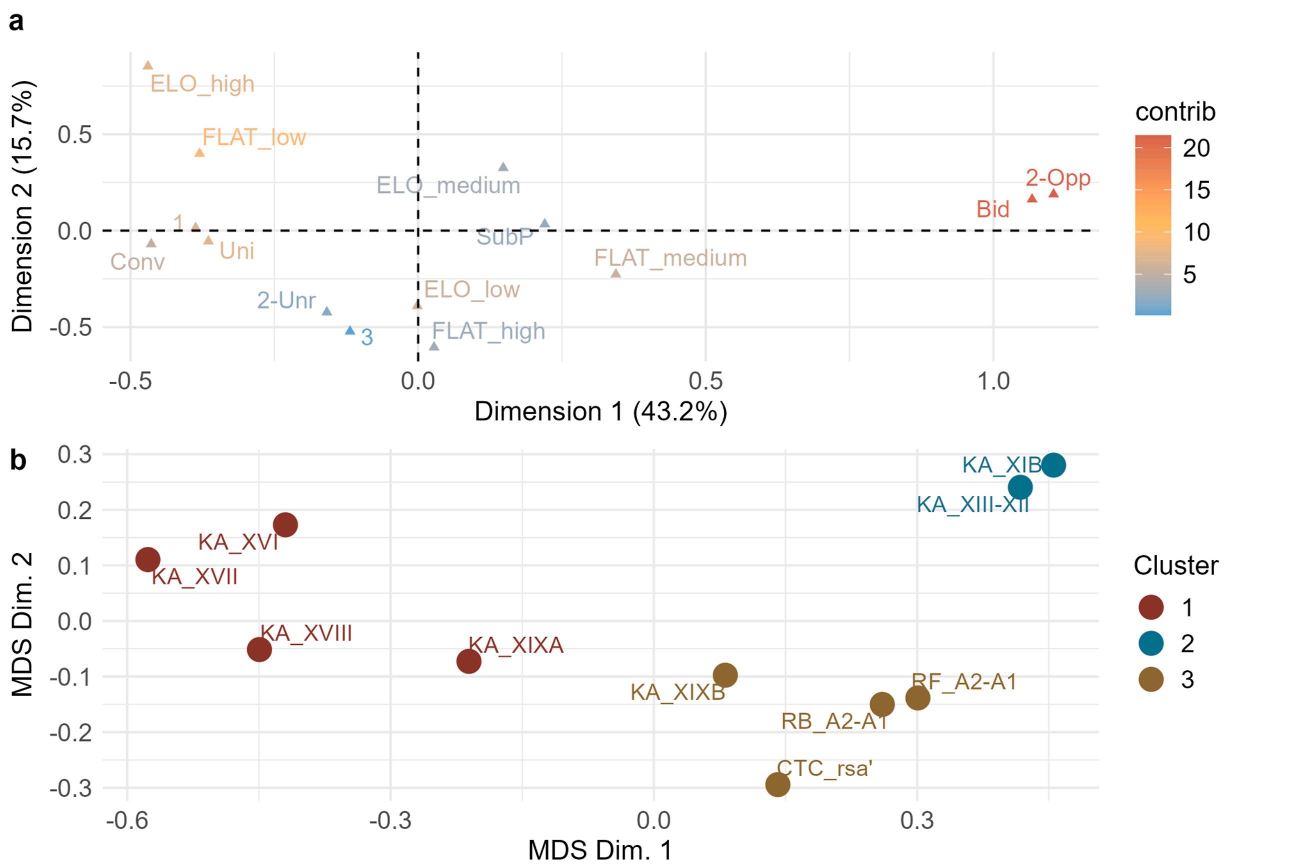

Figure 10. Laminar core analysis. **a.** Multiple correspondence analysis (MCA) plot displaying the contribution of the variable categories to the definition of the first and second dimensions. The color gradient (see the legend for color coding) represents the percentage of the contribution. **b.** Multidimensional scaling (MDS) plot showing the spatial relationships between the identified clusters, which are color coded. Please note that the spatial arrangement of the assemblages in the MDS plot does not directly correspond to the MCA plot in panel **a** as the MDS is based on the pairwise distances between assemblages, whereas the MCA plot is based on the dimensional reduction of categorical variables. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

column) when there was substantial overlap between most or all members of the groups. 'Exceptions' (third column) indicate cases where a single assemblage from one group clustered with another group, while the remaining assemblages clustered closely only with each other. Our comparative analysis of lithic assemblages from Ksar Akil (layers XIXB–XIB) and the PA sites of Bombrini, Castelcivita, and Fumane reveals distinct technological differences throughout all stages of the reduction sequence. These findings suggest a need to reassess both the internal variability within the Ahmarian and its hypothesized connection to the European PA. Evidence derived from the analysis of blanks, cores, and tools reveals no close, across-the-board technological affinities between the PA and any specific layer at Ksar Akil. Conversely, the marked technological consistency across PA assemblages indicates a high level of similarity in technological practice among foraging groups in Italy, despite variation in environmental settings and raw material availability. These results challenge the hypothesis that lithic technology provides evidence for population movements or the inter-regional transmission of learned behaviors from the Levant to Europe at this particular period.

The northern Ahmarian layers XIXB–XVI at Ksar Akil—those most often argued to be associated with the PA—exhibit the greatest technological divergence from it. In contrast to the PA, which is a bladelet-focused industry (Bon et al., 2010; Falcucci et al., 2017; Teyssandier, 2023), these layers prioritize blade production. Bladelets occur secondarily, likely as by-products of extended core reduction. Although bladelets may have been under-represented due to sampling biases during the Ksar Akil excavations, similar trends are evident at other northern Ahmarian sites, such as Üçağızlı (layers C and B1–3) and Manot (area C, layers 7–6) (Kuhn et al., 2009; Abulafia et al., 2021). At these sites, bladelet-sized pieces were produced but do not seem to have been the primary objective. Furthermore, the so-called El-Wad points from Ksar Akil (Ohnuma, 1988) and Üçağızlı (Eren and Kuhn, 2019) are typically manufactured on blades, contrasting with the PA, where Dufour types are almost exclusively made from bladelet blanks (Falcucci et al., 2018).

Our findings also indicate a progressive shift in core platform management within the northern Ahmarian layers at Ksar Akil. This transition involves a move from the use of hard hammer percussion with frequent platform faceting (layers XIXB–XVIII) to marginal direct percussion, possibly employing soft hammers or punches. This shift is marked by the adoption of plain striking platforms and steep striking angles, a key feature of Upper Paleolithic blade production across Eurasia (Bar-Yosef and Kuhn, 1999). This reduction method facilitates the production of elongated, slender blanks with consistent thickness along their lengths (Pigeot, 1987; Inizan et al., 1995; Eren et al., 2008). Notably, similar knapping strategies were already employed during the Châtelperronian (Roussel et al., 2016) and, to a lesser extent, the Uluzzian (Rossini et al., 2022; Marciani et al., 2025) in Europe.

The observed changes in platform management strategies within the northern Ahmarian layers at Ksar Akil warrant further investigation as they may reflect a gradual technological transition

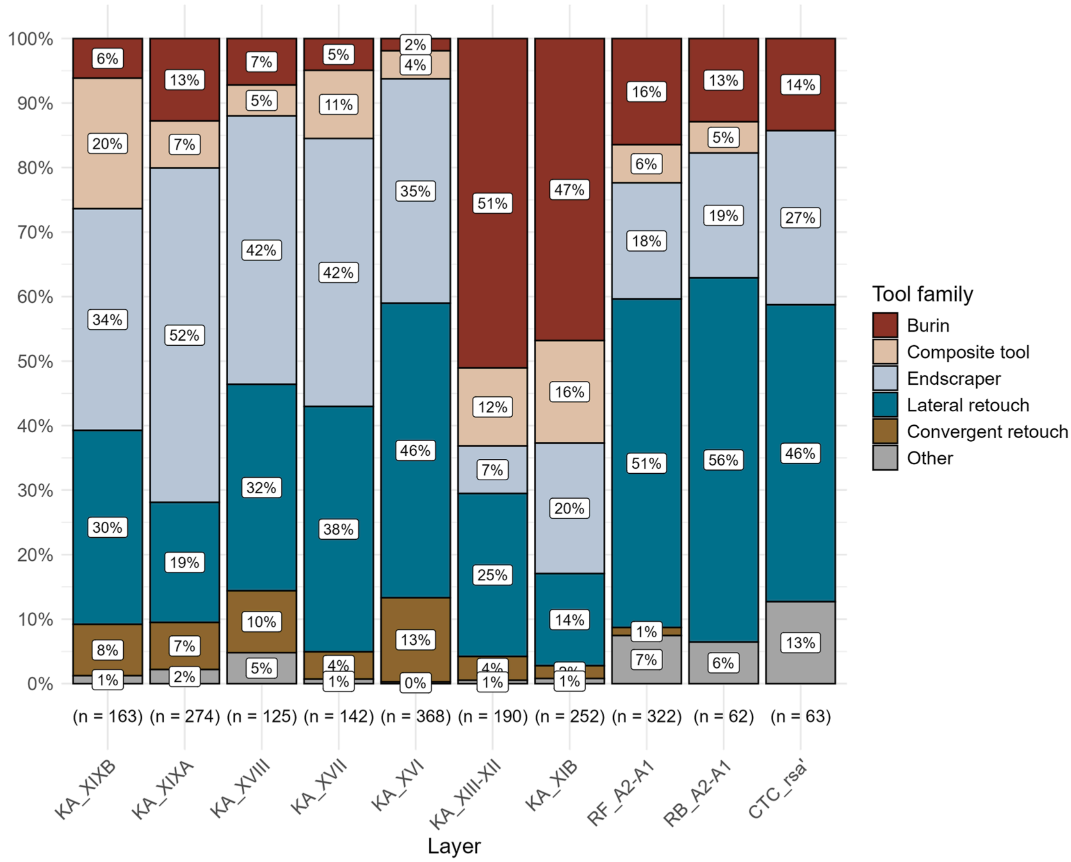

Figure 11. Bar chart showing the percentage distribution of tools (i.e., tools and core-tools), grouped into macrocategories, across the studied assemblages. The distribution is based on the minimum number of flaked products, excluding retouched bladelets from the quantification. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

from the IUP (Leder, 2018), as noted by several scholars (Bergman, 1988; Ohnuma, 1988; Williams and Bergman, 2010). Our study, for example, identified a pattern of gradual change in percussion techniques, accompanied by a more abrupt shift in bidirectional flaking methods. Notably, the detected clusters do not consistently group the lower Ahmarian layers together, possibly suggesting nonsynchronous shifts across the different lithic domains. Interestingly, Kuhn (2004) documented continuity in terms of raw material economy between IUP and northern Ahmarian assemblages at Üçağızlı, noting that changes in blade production strategies were not linked to shifts in raw material use. Instead, these changes appear to have occurred within the Ahmarian itself (Kuhn, 2013), reflecting a change from provisioning individuals to provisioning the site (see Kuhn, 1995).

The stratigraphic and technological links between the IUP and the Ahmarian *sensu lato* across the Levant have led several researchers to suggest that the IUP served as a precursor to the Ahmarian (e.g., Tostevin, 2003; Tostevin, 2013; Goring-Morris and Belfer-Cohen, 2018; Boaretto et al., 2021). Our findings offer partial support for this hypothesis. While the excavation techniques applied at Ksar Akil may have influenced the perception of a gradual technological transition (Zilhão et al., 2024), we found that layer XX contains very few lithics, suggesting a potential separation between different accumulation events. This stratigraphic distinction may thus provide some evidence for the partial integrity of the lower Ahmarian layers at Ksar Akil.

The analysis of core exploitation strategies and dorsal surface convexity provides critical evidence regarding both the internal variability within the northern Ahmarian and post-Ahmarian layers at Ksar Akil and the technological differences between these layers and the PA. Additionally, these analyses highlight the significant role played by raw material variability across the studied regions. Scar directionality data indicate that the PA is distinct from layers XVIII–XVI at Ksar Akil, which exhibit intensive bidirectional flaking—a pattern also confirmed through the core analysis. In contrast, both the lower layers (XIXB–XIXA) and the upper layers (XIII–XIB) at Ksar Akil emphasize unidirectional flaking, bringing them closer in this respect to the PA. Interestingly, within the PA, variability appears to be influenced by blank size. Smaller blanks form a distinct cluster, while larger blanks exhibit different characteristics, likely due to varying reduction intensities. Among the PA sites analyzed, Fumane demonstrates closer affinities to Ksar Akil's upper layers (XIII–XIB) in terms of direction of core exploitation than to Bombrini or Castelcivita.

These differences are strongly linked to both the PA's reduction procedures and the diverse raw material procurement strategies of each site. Specifically, the assemblage from Fumane, with access to larger and higher-quality raw material nodules, shows greater capacity for blade production than Bombrini and Castelcivita, where production of blade-sized blanks was more restricted by raw material size and availability. At Fumane, core refits also indicate exclusive blade production (Falcucci et al., 2017), with tools for activities such as hide working often manufactured on blades (Aleo et al., 2021). In contrast, at Bombrini, cores were often imported in preinitialized forms and blade production was largely limited to the maintenance of bladelet cores (Falcucci et al.,

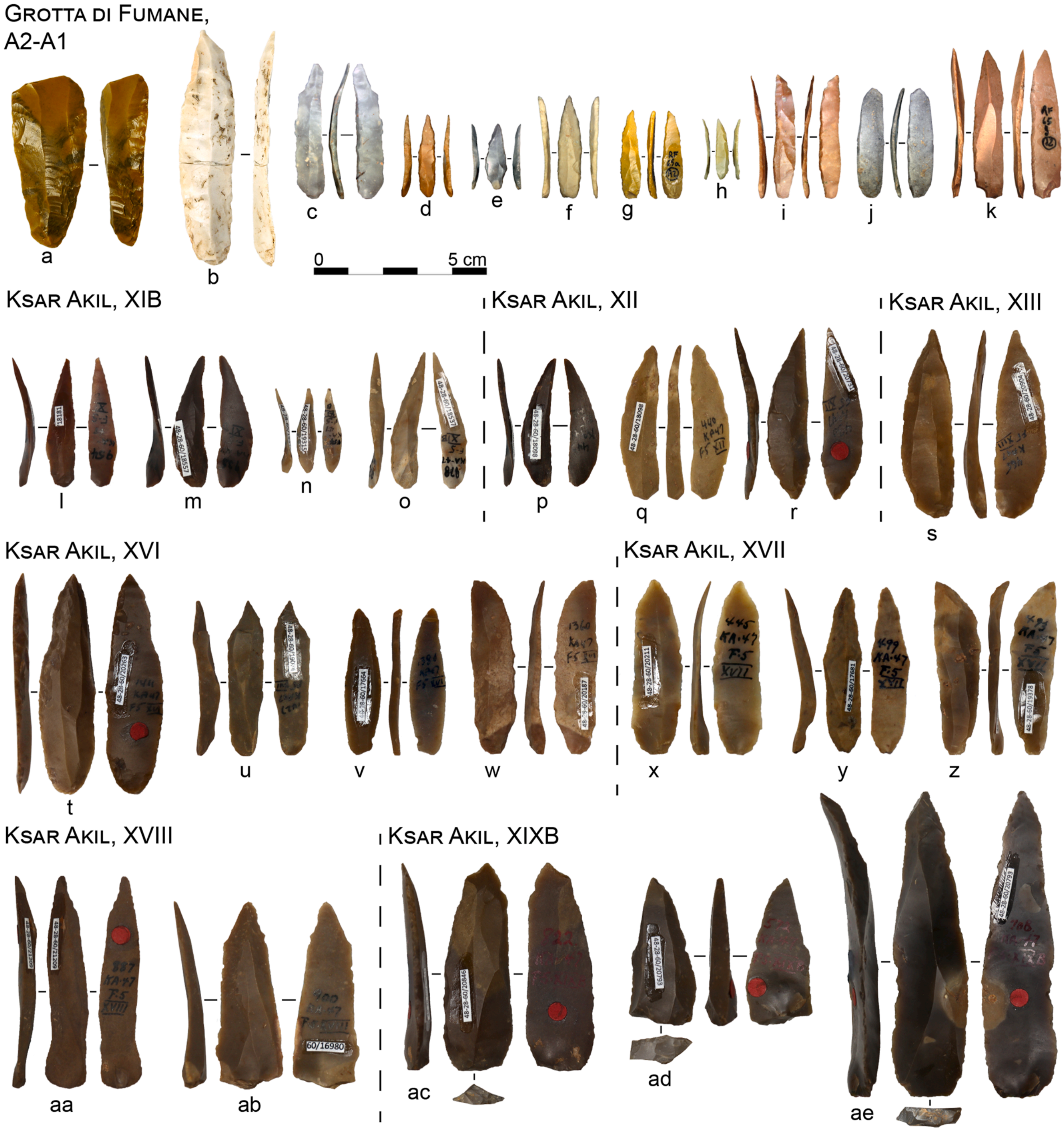

Figure 12. Examples of blades and bladelets with lateral or convergent retouch from Grotta di Fumane (**a**–**k**) and the Ksar Akil sequence (**l**–**ae**), sorted by site and layer of provenience. a–b, s, u, w–x, z, ab–ae = blades with direct retouch; c, j = bladelets with inverse retouch; d–f, h, l–r, v, y, aa = bladelets with direct retouch; g, i, k = bladelets with alternate retouch; t = a blade with alternate retouch. a and b are modified after Falcucci et al. (2017); c–k are modified after Falcucci and Peresani (2022). A list of the photographed Ksar Akil tools, along with their respective IDs, is available in the Zenodo research compendium *data* folder (Falcucci and Kuhn, 2025). Image by Armando Falcucci. Photos l–ae courtesy of the Peabody Museum of Archaeology and Ethnology, Harvard University (48-28-60/18181, 48-28-60/18557, 48-28-60/19315, 48-28-60/18537, 48-28-60/18098, 48-28-60/20731, 48-28-60/20904, 48-28-60/20263, 48-28-60/19074, 48-28-60/17664, 48-28-60/20187, 48-28-60/20211, 48-28-60/17681, 48-28-60/19378, 48-28-60/21209, 48-28-60/16980, 48-28-60/20846, 48-28-60/20793). Permission granted for use in this publication only; any reuse requires Peabody Museum approval.

2025a). The geological differences between these sites (see Section 3.2) further explain the variability in core volume and blank size within PA assemblages.

Several studies have demonstrated that PA core reduction systems primarily aimed to produce bladelets (Normand and Turq, 2005; Santamaría, 2012; Roussel and Soressi, 2013; Tafelmaier, 2017; Chu et al., 2022; Falcucci et al., 2024a). Cores were maintained through lateral blanks designed to isolate narrow flaking surfaces from which relatively straight bladelets were detached (Falcucci and Peresani, 2018). These maintenance blanks were often larger than the bladelets sought by toolmakers. Lombao et al. (2023) observed that PA core morphologies are markedly influenced by these maintenance strategies. Likewise, a 3D geometric morphometric study conducted at Fumane found that PA blades and bladelets could be differentiated based on their degree of lateral edge convergence and profile straightness. Blades detached during early core reduction and especially during core maintenance accounted for most of the observed variability (Falcucci et al., 2022).

In terms of dorsal surface convexity, PA assemblages also differ markedly from Ksar Akil's upper layers, despite them sharing a tendency for unidirectional flaking. Layers XIII–XIB show a

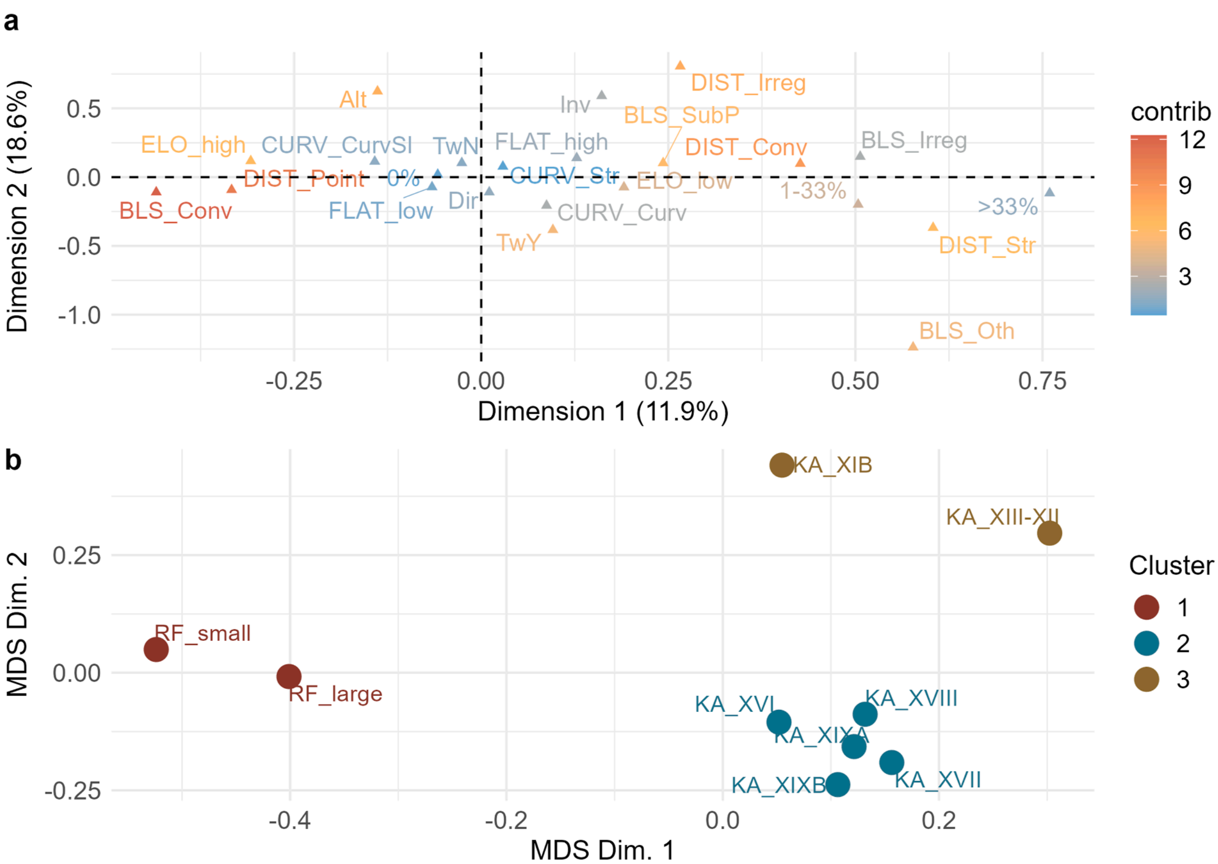

Figure 13. Laterally modified tools analysis. **a.** Multiple correspondence analysis (MCA) plot displaying the contribution of the variable categories to the definition of the first and second dimensions. The color gradient (see the legend for color coding) represents the percentage of the contribution. **b.** Multidimensional scaling (MDS) plot showing the spatial relationships between the identified clusters, which are color coded. Please note that the spatial arrangement of the assemblages in the MDS plot does not directly correspond to the MCA plot in panel **a** as the MDS is based on the pairwise distances between assemblages, whereas the MCA plot is based on the dimensional reduction of categorical variables. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

strikingly high number of blanks with twisted profiles, regardless of size. In PA sites such as Bombrini, twisted profiles are more commonly found on blades, where they are linked to core maintenance during bladelet production. At Ksar Akil, instead, twisted blanks appear to have been a sought-after product, as indicated by the similar twisting indices for both blanks (SOM Fig. S33) and laterally modified tools (SOM Fig. S62).

The lateral retouching of PA blanks follows a consistent pattern characterized by the selection of blanks from optimal core reduction stages and the application of inverse, alternate, and direct retouching. The frequency of different retouch types in the PA varies across Europe, and such regional variability may reflect functional or chronological differences. For instance, direct retouch is prevalent in the Fumane PA assemblage but is uncommon elsewhere in Western Europe, where inverse retouch is more typical (Falcucci et al., 2018). These findings challenge even further proposed technological links between the PA and the Ahmarian *sensu lato*, which have often been based on comparisons between Font-Yves points in the PA and El-Wad points in the Ahmarian Mellars (2006a). Retouch extension data reveal key differences: Ahmarian laterally modified blanks generally exhibit partial retouch (SOM Fig. S76), a feature observed by Gennai et al. (2023) also in southern Ahmarian assemblages, in sharp contrast to the PA. Furthermore, and perhaps most importantly in terms of functionality and hafting strategies, laterally retouched tools in the PA are primarily made on bladelets, whereas the Ksar Akil data indicate that large blades were more commonly selected in the northern Ahmarian for manufacturing these tools.

Finally, core analysis further underscores the technological distinctions between Ksar Akil's lower and upper layers and the PA. In layers XIII–XIB, bladelets were produced mainly from carinated burin cores, which yield twisted blanks (Lucas, 1999; Le Brun-Ricalens and Brou, 2003). These features have also been documented in other excavation square units at Ksar Akil (Bretzke et al., 2017). Likewise, Bergman (1987) attributed the high frequency of twisted blanks to an elevated burin index in these layers. Although burin cores were sometimes employed for bladelet production in the PA (Bordes, 2006; Falcucci and Peresani, 2018), they were not used for systematic production of twisted blanks through carinated reduction. The limited use of carinated cores in the PA distinguishes it from later Aurignacian phases, where twisted bladelets detached from carinated burins are a defining characteristic (Lucas, 1997; Michel, 2010; Dinnis et al., 2019), reflecting markedly divergent technological trajectories in the Levant and Europe.

5.2. No evidence for a northern-to-southern Ahmarian shift at Ksar Akil and distinctive chronological and technological features of the Protoaurignacian

The findings of this study not only undermine the hypothesis of a technological link between the northern Ahmarian and post-Ahmarian layers at Ksar Akil and the PA but also challenge the proposed technocultural succession from the northern to southern Ahmarian in the region. Layers XVII–XVI at Ksar Akil, traditionally seen as the classic Ahmarian (Kuhn et al., 2009), are

Table 5
Summary of the relationships between Protoaurignacian assemblages and Ksar Akil layers XIXB–XIB, as revealed by multiple correspondence analysis (MCA) of the five lithic domains presented in the Results section.

Attribute set	Protoaurignacian clusters with	Protoaurignacian is most distant from	Exceptions
Platform maintenance	KA_XIB–KA_XVII	KA_XVIII–KA_XIXB	None
Direction of core exploitation	None	KA_XVI–KA_XVIII	RF_large clusters with KA_XIB–KA_XIII and KA_XIXB–KA_XIXA
Dorsal surface convexity	None	All KA assemblages	RB_large clusters with KA_XIB–KA_XIII
Laminar cores	None	KA_XVI–KA_XVIII	KA_XIXB clusters with all PA assemblages
Blank selection and retouching	None	All KA assemblages	RB and CTC were not analyzed due to the limited sample size

The column 'Protoaurignacian clusters with' indicates the Ksar Akil assemblages that cluster with Protoaurignacian sites, while the column 'Protoaurignacian is most distant from' highlights the Ksar Akil assemblages that diverge most from the Protoaurignacian. The 'Exceptions' column lists deviations from the main patterns identified by the MCA. Abbreviations used throughout the paper are retained: PA refers to Protoaurignacian, KA to Ksar Akil, CTC to Grotta di Castelcivita, RF to Grotta di Fumane, and RB to Riparo Bombrini. Additionally, RF_large and RB_large denote blanks larger than 25 mm, based on the size cutoff used in the comparative analyses.

technologically distinct from the layers above, despite suggestions by some researchers of a gradual development from the northern to the southern Ahmarian (Kadowaki et al., 2015; Slimak, 2023). The presence of the low-density intervening layers XV–XIV, collectively known as Stone Complex 2, is particularly significant as it clearly prevented stratigraphic mixing between these assemblages, as corroborated by the sharp, technological shift observed.

The layers above Stone Complex 2 were initially included in the Levantine Aurignacian A due to the abundance of carinated tools (Besançon et al., 1977; Ohnuma and Bergman, 1990). However, later studies labeled layers XIII–XII as 'unassigned Upper Paleolithic' assemblages with some affinities to the southern Ahmarian, with Bergman et al. (2017) discussing their cultural taxonomic limbo. Chronological and technological variability in these assemblages has been the subject of extensive debate. Establishing precise chronological frameworks in the Levant remains a challenge, particularly due to difficulties in obtaining reliable radiocarbon dates (Bosch et al., 2015). Many dates for southern Ahmarian open-air sites in the Negev and Sinai are considered minimum estimates (Gilead, 1991; Richter et al., 2020), and numerous samples were dated prior to the adoption of modern pretreatment chemistry (Kadowaki et al., 2015; Stutz et al., 2015), which may significantly distort results, particularly for samples older than 40 ka (Pigati et al., 2007). Similar concerns apply to northern Ahmarian sites, such as Üçağızlı, where radiocarbon determinations may underestimate the true age of deposits by 3500–5000 years (Kuhn et al., 2009).

Despite these challenges, there is a general tendency to consider the southern Ahmarian as chronologically younger than the northern Ahmarian facies from the Mediterranean zone (Kadowaki et al., 2015; Abulafia et al., 2021; Gennai et al., 2023). An OSL dating study at Boker Tachtit concluded that the IUP in the Negev, which predates the southern Ahmarian, overlaps chronologically with the northern Ahmarian in Mediterranean regions, suggesting distinct cultural trajectories for these northern and southern variants (Boaretto et al., 2021), as previously suggested for Tor Sadaf (Fox and Coinman, 2004). Evidence from Wadi Aghar in southern Jordan further indicates an IUP presence dated to 36–39 ka (Kadowaki et al., 2019). These interpretations are however markedly relying on the old chronological estimates for the northern Ahmarian layers at Kebara (Rebollo et al., 2011) and Manot (Alex et al., 2017), which have faced serious scrutiny regarding stratigraphic integrity (Zilhão, 2013; Zilhão et al., 2024).

To refine the chronological framework of the PA and the Ahmarian, we compiled an extensive dataset of radiocarbon (shell and charcoal), OSL, and thermoluminescence dates from sites and layers attributed to both the northern and southern Ahmarian, as well as the PA (SOM Table S47). We applied a nonparametric kernel density estimates (KDE) model (Bronk Ramsey, 2017) using the OxCal v.4.4 software (Bronk Ramsey, 2009; Bronk Ramsey and Lee, 2013) with the INTCAL20 and MARINE20 calibration curves (Heaton et al., 2020; Reimer et al., 2020) to summarize the distribution of these dates (see OxCal code in SOM Note 2). Furthermore, we included the dates of layers XII and XI at Ksar Akil to compare them with the distribution of the southern Ahmarian.

First, the results reveal that the PA exhibits a relatively narrow chronological range, with dates forming a tight probability density between 42 and 40 ky cal BP (Fig. 14). There is a significant decline in density after 39 ky cal BP, indicating a well-defined temporal boundary for PA assemblages. In contrast, the northern Ahmarian shows a broader distribution, with no clear peaks in the KDE model. Instead, this model is characterized by consistently medium to high density between 47 and 38 ky cal BP, likely reflecting the variability in estimations obtained from sites such as Kebara and Manot on the one hand and Ksar Akil and Üçağızlı on the other. The southern Ahmarian also displays a wide chronological range, though the KDE model reveals a left-skewed peak between 39 and 37 ky cal BP. This distribution confirms the younger ages of the southern Ahmarian, based on available evidence, compared to both the PA and northern Ahmarian. Kadowaki et al. (2015) discussed how most southern Ahmarian dates were obtained before the advent of accelerator mass spectrometry (AMS) dating. By considering only AMS-derived dates, the authors noticed that the chronological range narrows, yielding younger estimations that are in line with our KDE model. This observation also aligns with the most recent dates obtained at Al Ansab 1, which range from 39.5 to 36.4 ky cal BP (Richter et al., 2020). Finally, layers XII and XI at Ksar Akil plot after 40 ky cal BP, within the densest area of the southern Ahmarian, suggesting statistical chronological overlap between these technological systems.

While these data indicate some chronological overlap between the PA and the northern Ahmarian and between the southern Ahmarian and layers XII–XI at Ksar Akil, they also emphasize the broader chronological spread of Levantine assemblages than the PA, partly due to the high sigmas associated with the Levantine dates. This variability underscores the current unreliability of chronological evidence and highlights the need to rely primarily on material culture data, particularly lithic evidence. For this reason, we conducted a detailed literature review to further investigate potential links between southern Ahmarian assemblages, layers XIII–XIB at Ksar Akil, and the PA. Layers XIII–XIB at Ksar Akil have been explicitly associated with the southern Ahmarian based on the use of unidirectional knapping strategies and the miniaturization of laminar blanks (Kadowaki et al., 2015; Demidenko and Hauck, 2017; Slimak, 2023). However, these features are not unique to these assemblages. The most significant

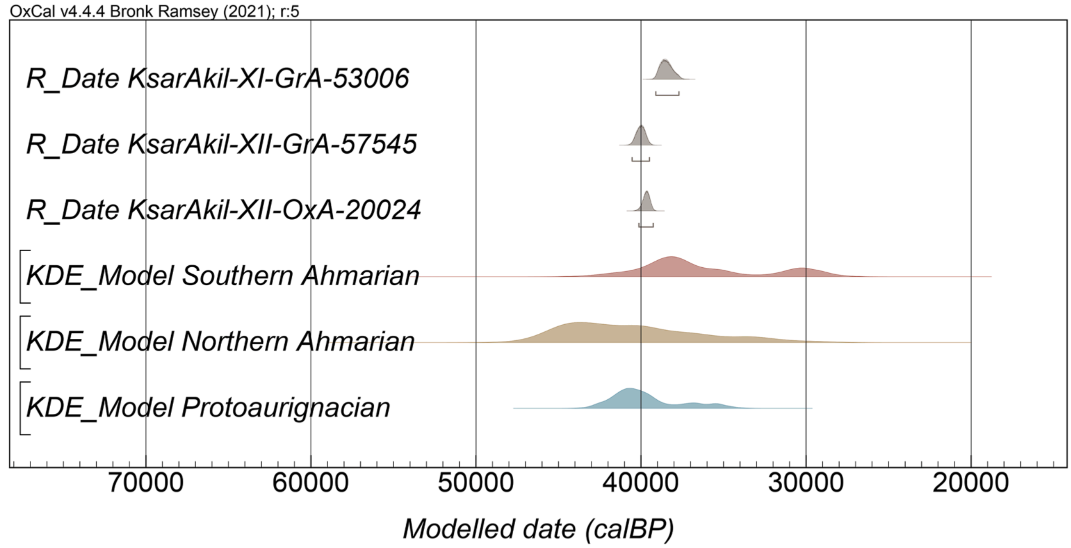

Figure 14. Kernel density estimate (KDE) models for the Protoaurignacian, northern Ahmarian, and southern Ahmarian, and radiocarbon estimates of layers XII and XI from Ksar Akil from Douka et al. (2013) and Bosch et al. (2015) . A list with of all the dates used in the KDE models along with the bibliographic sources are listed in SOM Table S47.

difference is the use of multiple burins and carinated burins at Ksar Akil to produce twisted blades and bladelets—a technology uncommon in the southern Ahmarian from the semiarid zones (Gennai et al., 2023).

In the southern Ahmarian, cores discarded at various stages of the reduction sequence almost never exhibit the morphological features of carinated burins. Only a handful of carinated burins have been identified, such as at Lagama VII and Lagama XII, where a few small bladelets were noted to correspond well with the bladelet negatives on these burins (Bar-Yosef and Phillips, 1977). Interestingly, the Lagama sites (i.e., V—VIII, XI—XII, and XV—XVI) exhibit significant typological diversity, particularly in the proportions of retouched bladelets, El-Wad points, and other tools such as burins and endscrapers, despite maintaining an overall technological uniformity. In all cases, bladelet production relied predominantly on unidirectional single-platform cores, with bidirectional cores being relatively uncommon. Gilead (1983) suggested that these typological differences reflect varying site functions and land-use strategies within the same broader technological tradition.

Similarly, other southern Ahmarian sites, including Nahal Nizzana XIII in western Negev (Davidzon and Goring-Morris, 2003), Tor Sadaf in Wadi al-Hasa (Fox and Coinman, 2004), Boker A in central Negev (Monigal, 2003), Al-Ansab 1 in Wadi Sabra (Richter et al., 2020; Parow-Souchon et al., 2021; Gennai et al., 2023), and Abu Noshra I and II in southern Sinai (Phillips, 1988), are characterized by the consistent use of unidirectional blade and bladelet cores with narrow flaking surfaces and converging edges, producing straight to slightly curved bladelets, as demonstrated best by extensive refitting studies at Nahal Nizzana XIII (Davidzon and Goring-Morris, 2003). At Tor Sadaf, for example, twisted debitage is not mentioned, and illustrations indicate the selection of relatively straight blanks. Similarly, there is no evidence of products typically associated with burin technology, such as burin spalls often used to initiate bladelet production (see Bataille and Conard, 2018). Simple burins are also absent in the tool inventory at Tor Sadaf (Fox, 2003).

At Boker A, laminar cores have flaking surfaces oriented along the longest axis of the raw material nodule and often retain a natural posterior crest (Monigal, 2003). Although burins constitute 16% of the tool assemblage—similar to the proportion found at Abu Noshra I (Phillips, 1988)—evidence of bladelet production on burins is limited to a single carinated burin and a few multiple burins (Jones et al., 1983). Interestingly, Jones et al. (1983) documented a high frequency of twisted blades (122 out of 291 items), along with evidence suggesting that both blades and bladelets were produced from the same cores—an attribute characteristic of laminar platform core technologies (Lombao et al., 2023). Twisted bladelets are instead uncommon at Boker A. This pattern is consistent with our findings for the PA, where blade twisting was linked to maintenance operations on bladelet cores. A distinctive feature of Boker A, uncommon in the Ahmarian *sensu lato*, is the frequent use of inverse marginal retouching—often on the right side—to modify bladelet edges. This technological attribute contributed to the classification of Boker A as an assemblage closely related to the PA (Mellars, 2006a).

A key site of the southern Ahmarian is Al-Ansab 1, dated to approximately 39 to 37 ky cal BP (Richter et al., 2020). As observed at other southern Ahmarian sites, laminar production at Al-Ansab 1 is predominantly based on narrow-fronted cores, with carinated cores being rare (Gennai et al., 2023). While the narrow-fronted core shape may be influenced by the size of available raw material nodules, this system was also applied to wider nodules, indicating strong technological norms guiding the operational sequence. At Al-Ansab 1, 20% of bladelets and 26% of blades are classified as twisted (Gennai et al., 2023). However, these twisted blanks are once again associated with core maintenance operations rather than being intentionally sought after products, as also noted by Parow-Souchon et al. (2021). In terms of modification, most laterally retouched blanks exhibit direct retouching, while only three small bladelets show evidence of inverse retouching (Gennai et al., 2023).

This review highlights that the only parallels between the southern Ahmarian, layers XIII—XIB at Ksar Akil, and the PA lie in the emphasis on bladelet production, while striking technological differences persist in other domains. The post-Ahmarian layers at Ksar Akil are dominated by burin-core technologies, with toolmakers primarily aiming to produce twisted blanks. These technological differences cast serious doubt on the hypothesis of a direct succession between northern and southern Ahmarian facies at Ksar Akil. We argue instead that the technological shift at Ksar Akil is part of a broader pattern observed at sites across both

Mediterranean and inland regions of the northern Levant. This evidence is particularly significant as it underscores shared regional technological trajectories rather than an isolated development.

At Yabrud II, the excavations by Rust (1950) revealed a sequence spanning the IUP (layer 6), the Ahmarian (layer 5), and several bladelet-dominated assemblages (layers 4 to 1) (Pastoors et al., 2008). While layer 1 exhibits Levantine Aurignacian features, layers 4 to 2 have been compared by Demidenko and Hauck (2017) to the Ksar Akil phase 3 (layers XIII—XII from the 1947—1948 excavations). This cultural association turns around the presence of carinated burins for bladelet production and twisted laminar blanks and tools. Yabrud II is situated only around 100 km from Ksar Akil, increasing the plausibility of shared technological traditions. Supporting evidence of interregional connections in this period includes an obsidian tool recovered from Yabrud II layer 4, which was made from the same Turkish raw material source (700 km away as the crow flies) as a burin from Ksar Akil layer XIA (Frahm and Tryon, 2019). Yabrud II is not the only site in the Qalamoun region to exhibit a technological shift from blade production to twisted bladelet production. Similar patterns have been documented at Baaz Rockshelter, where Bretzke et al. (2017) identified this shift around 38 ky cal BP (Deckers et al., 2009).

It is worth noting that Kadowaki et al. (2015) identified similarities between Ksar Akil phase 4 (layers XC—XI from the 1947-1948 excavations) and the lithic assemblage recovered from Wadi Kharar 16R in inland Syria. A single radiocarbon determination dates this site to 38.6—37 ky cal BP. The authors observed a marked miniaturization of this assemblage, noting similarities with Ksar Akil phase 4 in terms of blank shapes and point retouching. The percentage of twisted blanks at Wadi Kharar 16R (19%) is lower than in the Ksar Akil layers XIII—XIB but aligns more closely with data from layer XC, as described by Williams and Bergman (2010). Later, Kadowaki (2018) noted that Wadi Kharar 16R exhibited mixed features of the southern Ahmarian and Levantine Aurignacian due to the presence of twisted debitage, highlighting challenges in establishing clear connections between these assemblages. In this regard, it is not entirely clear why layers XIII—XI at Ksar Akil were excluded from the comparative study. Our analyses suggest that these industries may not align with the scenario proposed by Kadowaki et al. (2015) concerning links between Ksar Akil phase 4 and the southern Ahmarian.

Overall, the technological trajectories of the Upper Paleolithic in the Levant exhibit pronounced regional variability despite geographic proximity, revealing a complex pattern of technocultural developments likely shaped by both cultural and environmental factors. This issue also highlights the need for further discussion regarding the chronological, geographical, and technological relationships between the northern and southern variants of the Ahmarian. While a southern Ahmarian assemblage was not included in our comparative analysis, it is noteworthy that Gennai et al. (2021) identified some technological affinities between the PA and southern Ahmarian systems, despite significant chronological differences between the compared assemblages, a finding further confirmed by subsequent comparative studies (Gennai et al., 2025). This further reflects a complex technocultural mosaic in the Levant. From the end of the IUP onward, the Levantine Upper Paleolithic record becomes considerably more heterogeneous than that of Western Europe (Kadowaki et al., 2019), where technocultural trajectories, particularly from the onset of the Aurignacian, appear relatively homogeneous (Maier et al., 2022). Given this complex cultural landscape, we argue that there is currently limited evidence to support substantial cultural connections between the Ahmarian *sensu lato* or the 'post-Ahmarian' industries of the Near East and the early stages of the Upper Paleolithic of Europe.

5.3. Dispersal, diffusion, and convergence in the origins of the Protoaurignacian

Our comparative study of PA and northern Ahmarian assemblages reveals very limited similarities between them. Although both are dominated by laminar technology, the details of the technologies from the ways cores were exploited and the types of percussion used to the products of blank production (i.e., blades vs bladelets) are highly divergent. Resemblances between the PA and the 'post-Ahmarian' at Ksar Akil are equally tenuous. The widespread hypothesis that the PA represents a dispersal of amHs groups producing Ahmarian technologies from the Levant into southwest Europe appears to have little support from the archaeology. To be clear, we are not denying that populations of amHs did disperse from Africa into Europe via the eastern Mediterranean Levant: Genetic evidence makes it abundantly clear that this did happen, at some time. However, our study indicates that the PA is not a direct proxy for such a dispersal event.

Regarding the archaeological evidence, these findings leave us with the question of where the PA did originate. If it does not represent demic expansion from the Levant, perhaps we ought to seek local origins. The Châtelperronian is one EUP or 'transitional' assemblage that predates the PA and overlaps significantly with it in its geographic distribution. According to Roussel (2013), there are technological distinctions between the PA and the Châtelperronian in Europe, though they were not substantiated by a quantitative 3D-based analysis (Porter et al., 2019). Importantly, both technocomplexes share common features—most notably, the use of volumetric platform cores to produce laminar blanks using marginal freehand percussion. Moreover, recent technological studies found that bladelets were frequently produced in the Châtelperronian and at some sites—Quinçay, Ormesson, and Aranbaltza II—were modified into Dufour types (Roussel et al., 2016; Bodu et al., 2017; Rios-Garaizar et al., 2022). Roussel et al. (2016) argued that the presence of Dufour bladelets in the Châtelperronian at Quinçay could be explained by stimulus diffusion (Kroeber, 1940) from the PA. However, the geographic distribution and chronological data on PA sites challenge this hypothesis (Zilhão et al., 2024). In the end, the shift from the Mousterian to the Châtelperronian appears more pronounced than any technological break between the Châtelperronian and the PA (Teyssandier, 2024).

Of course, the Châtelperronian is usually attributed to Neanderthals, whereas the PA is thought to be a product of amHs. However, this does not mean that they cannot be related through processes of cultural transmission. First, as discussed in an earlier section of this paper, the fossil evidence linking most EUP or 'transitional' industries to specific hominin taxa is equivocal. Even the presumed Neanderthal authorship of the Châtelperronian has been questioned. It seems that western Eurasia was a zone of population mixing and hybridization between 50 ka and 35 ka. Genetic and fossil evidence points to frequent introgression between Neanderthal and amHs populations. Such observations call into question attempts to attribute archaeological assemblages to a single 'pure' hominin taxon. If groups were exchanging genes, it is a small stretch to imagine that they might also have been exchanging technological knowledge. And there is no reason to think that information should not have been shared in two directions (Greenbaum et al., 2018).

We are not in a position to test the proposition whether the Châtelperronian was ancestral to or at least influenced the development of the PA. However, it is a viable alternative to the now-undermined Levantine origin hypothesis. We note that some scholars have linked the Châtelperronian to the Ahmarian layers XVI–XVII at Ksar Akil, citing similarities in bidirectional knapping techniques and morphometric variability of backed blades (Slimak, 2023). While we lack the data to evaluate this proposition, this association faces significant obstacles. The Châtelperronian appears to predate the northern Ahmarian almost everywhere, and moreover, there are no known Châtelperronian sites outside France and northern Iberia, highlighting a striking geographic gap between the makers of the two industries. Additionally, no quantitative study has yet substantiated the proposed link (see also discussion in Djakovic et al., 2024).

One of the main distinctions between the Châtelperronian and the PA is the much greater emphasis on production of small bladelets in the latter. Although Châtelperronian assemblages may contain bladelets, they are a great deal more common in the PA. Technologically, however, the transition from blades to bladelets is a fairly 'easy' one. The miniaturization (see Pargeter and Shea, 2019) of lithic assemblages is the key feature of the Upper Paleolithic and Later Stone Age across the globe. Within Europe and the Near East, the miniaturization of lithic technologies, the fluorescence of bladelet production, was achieved through diverse technological strategies and procedures (e.g., volumetric wide-faced or narrow-fronted cores and carinated cores). In the Levant, the adoption of bladelet technologies is associated with increased lithic cutting-edge productivity, coinciding with changes in platform preparation techniques in the EUP (Kadowaki et al., 2024). In Europe, this process accelerated with the development of the PA but, importantly, began earlier in the Middle Paleolithic, as evidenced by the growing evidence of industries characterized by bladelets and micropoints (Slimak et al., 2022; Carmignani and Soressi, 2023; Carmignani et al., 2024; Sánchez-Yustos et al., 2024).

In the PA, miniaturization is closely tied to the emergence of multicomponent projectile technology (Bon et al., 2010; Teyssandier et al., 2010), with bladelets likely hafted as barbs (Porraz et al., 2010; Pasquini, 2013). This contrasts with earlier periods, where lithic tools were typically hafted distally (Sano et al., 2019; Wiśniewski et al., 2022; Metz et al., 2023). We argue that the increased reliance on composite tools with multiple stone insets, coupled with changes in mobility patterns (see also Kadowaki et al., 2021), was a major driver of lithic miniaturization (Kuhn, 2020). The manufacture of such tools required a high degree of standardization—a challenge for freehand knapping. A two-dimensional shape analysis study demonstrated significant differences in blade standardization depending on the knapping technique employed. Pressure flaking, for example, produced markedly more standardized blanks than direct or indirect percussion (Muller and Clarkson, 2023). Before the adoption of pressure flaking, toolmakers achieved standardization by reducing artifact size. This was confirmed by an analysis of over 100 assemblages spanning the Middle Pleistocene to the Holocene, which showed that, prior to the advent of pressure debitage, reducing the dimensions of artifacts allowed for greater dimensional tolerance (Kuhn and Shimelmitz, 2022). The need for efficient retooling of composite tools could have driven a series of parallel technological trajectories across the Mediterranean Basin. Retooling required lithic elements of similar size to minimize production costs, ultimately contributing to the widespread adoption of miniaturized technologies (Kuhn and Shimelmitz, 2022).

6. Conclusions

Substantial progress is being made in understanding the behavioral processes that led to the emergence of the Upper Paleolithic. While much attention has been given to the dispersal of amHs populations from Africa into Eurasia, recent research in human evolution is increasingly emphasizing the cultural and biological consequences of encounters between different human lineages in diverse environmental contexts. In this paper, we have demonstrated that lithic analysis continues to provide valuable evidence for critically examining purposed dispersal events and cultural transmission processes as it allows for a quantitative assessment of learned behaviors, particularly when comparisons are freed from the constraints of rigid cultural taxonomies (Shea, 2014). Through a comprehensive comparison of lithic technologies from northern Ahmarian and post-Ahmarian layers at Ksar Akil with PA assemblages from key sites in Italy, combined with an extensive review of the literature, we have shown that the long-held notion that the PA originated from Levantine Ahmarian technologies is unsupported. Although there are superficial similarities, the underlying suites of technological procedures are very different, suggesting convergence rather than diffusion or population expansion. Moreover, the potential technological foundations of the bladelet-dominated PA were already present in Europe prior to the emergence of the Ahmarian in the Levant. We propose that the PA is one expression of a widespread trend leading toward lithic miniaturization and that it may reflect technological convergence rather than demic expansion or direct cultural diffusion. The comparison between the European and Levantine EUP records reveals that although both regions developed bladelet technologies, these were not synchronous and were achieved through different core reduction strategies. This suggests a rather low level of cultural exchange, likely due to isolation by distance (Shennan et al., 2015), challenging models that exclusively rely on demic diffusion along an east-to-west gradient. The many advantages of strategies involving the hafting of multiple lithic insets into lightweight organic armatures for the production of weapons and other tools may have driven this technological shift. While we acknowledge that low levels of cultural interaction between highly mobile foraging groups may have marginally contributed to this process, the available evidence suggests that parallelism or convergence are the most likely explanations for similarities in lithic technology. This, in turn, underscores the need for more nuanced explanatory models that account for independent technological developments and specific environmental adaptations.

Declaration competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

Armando Falcucci: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Steven L. Kuhn:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization.

Data availability and reproducibility

The Ksar Akil dataset and all other datasets generated in this study are available in the associated research compendium on Zenodo (Falcucci and Kuhn, 2025): https://zenodo.org/doi/10.5281/zenodo.16932273. The Protoaurignacian datasets used in this study are available on Zenodo (Falcucci et al., 2024c, 2024d, 2025d) and were published alongside research papers on Grotta di Castelcivita (Falcucci et al., 2024a), Grotta di Fumane (Falcucci et al., 2024b), and Riparo Bombrini (Falcucci et al., 2025a). Data manipulation, visualization, and statistical analysis were performed in R v.4.3.1 (R Core team, 2023) and R Studio (Posit team, 2023). All scripts and necessary information to reproduce the results are provided in the Zenodo research compendium (Falcucci and Kuhn, 2025). The *renv* package (Ushey and Wickham, 2023) was used to create a reproducible environment, ensuring full reusability of our code and workflow. The SOM file was generated using R Markdown (Allaire et al., 2023).

Supplementary Online Material

Supplementary Online Material related to this article can be found at https://doi.org/10.1016/j.jhevol.2025.103744.

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