Quaternary Science Reviews 366 (2025) 109471

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Revisiting the Early Aurignacian in Italy: New insights from Grotta della Cala

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ARTICLE INFO

Handling Editor: Rivka Rabinovich

Keywords:
Early Upper Paleolithic
Henrich stadial 4
Campanian ignimbrite
Lithic technology
Osseous technology
Malacology
OSL and radiocarbon dating

ABSTRACT

Grotta della Cala in southern Italy is a key archaeological site spanning from the Middle Paleolithic to the Bronze Age. In the stratigraphic sequence close to the cave entrance, numerous artifacts associated with Aurignacian occupations were uncovered, including both lithic and organic materials. However, earlier interpretations were limited by challenges in dating the Upper Paleolithic layers and a lack of modern analytical methods for characterizing the finds. Recent excavations have refined the site's chronology and further explored the Aurignacian deposit. This study builds on this updated framework, offering an interdisciplinary reassessment that includes technological analyses of lithic assemblages and bone tools, along with a taxonomic examination of the marine shells. Many of these shells were intentionally perforated, suggesting symbolic behaviors linked to coastal resource exploitation. Lithic technology at the site is characterized by the systematic production of miniaturized bladelets from carinated cores, while osseous technology centers on the manufacture of split-based antler points, marking the southernmost occurrence of this tool type in Europe. The integration of new radiocarbon and optically stimulated luminescence dating allows us to confidently assign all analyzed sub-layers to the Early Aurignacian, a significant finding, given that no other sites in the region securely postdate the Campanian Ignimbrite (~40,000 years ago). As such, Grotta della Cala is a crucial site for understanding the lifeways of Aurignacian foraging groups in the aftermath of this super-eruption and during Heinrich Stadial 4. Our comparative analysis of Early Aurignacian sites across Italy provides a clearer understanding of regional variability and continuity between 40,000 and 37,000 years ago, contributing to the broader debate on the biocultural dynamics of the Upper Paleolithic in Europe.

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https://doi.org/10.1016/j.quascirev.2025.109471
Received 10 December 2024; Received in revised form 7 May 2025; Accepted 8 June 2025
Available online 10 July 2025

1. Introduction and research aim

Several cave sites across Europe provide exceptional preservation of multi-layered evidence of human occupations over time, making them ideal contexts for investigating the development of human behavior during the Pleistocene. In Europe, the rate of cultural change significantly intensifies during the early Upper Paleolithic (Kuhn, 2021; Teyssandier, 2024). This period is characterized by increased mobility and interconnectivity among foraging groups, as evidenced by the abundance of exogenous raw materials in stone tool production (e.g., across the Liguro–Provençal Arc: Bertola et al., 2018; Falcucci et al., 2025a; Grimaldi et al., 2014; Porraz et al., 2010) and the recovery of marine shells at sites located several hundred kilometers inland from coastlines (Peresani et al., 2019a; Taborin, 1993a; Vanhaeren and d'Errico, 2006). These developments are also reflected by broader shifts in composite technology and symbolic behavior, as well as by the intensification and diversification of osseous tool production (Arrighi et al., 2020c; Conard, 2009; d'Errico et al., 2012; Dutkiewicz et al., 2018; Kuhn and Shimelmitz, 2022; Liolios, 2006; Sano et al., 2019; Tartar, 2012; among many others).

The rich archaeological record south of the Alps and throughout the Italian Peninsula, combined with pivotal research conducted in recent years, provides an excellent context for tracing cultural trajectories. The first Upper Paleolithic technocomplex in Italy is the Uluzzian, which was initially identified at Grotta del Cavallo in the Uluzzo Bay, Apulia (Palma di Cesnola, 1989). While most Uluzzian sites are concentrated in southern and central Italy (Collina et al., 2020; Gambassini, 1997; Moroni et al., 2013, 2018; Rossini et al., 2022; Villa et al., 2018), a few have also been discovered in northeastern Italy (Peresani et al., 2016, 2019b). Notably, the Uluzzian is virtually absent in Liguria, northwestern Italy. Characterized by a distinctive lithic technology that heavily relies on the bipolar technique on anvil (Arrighi et al., 2020b; Delpiano et al., 2024; Rossini et al., 2022), the Uluzzian also exhibits unique hunting strategies (Sano et al., 2019), exploitation of faunal resources (Boscato and Crezzini, 2012), bone tool production (Arrighi et al., 2020c; d'Errico et al., 2012), and the use of marine shells (e.g., *Antalis* sp.) and coloring materials for symbolic purposes (Arrighi et al., 2020c; d'Errico et al., 2012).

The Uluzzian technocomplex lasted just over 2000 years, spanning from approximately 43,120 to 41,370 cal BP (with 68.2 % probability) (Higham et al., 2024). During its duration in southern Italy, the Uluzzian coexisted with the Protoaurignacian (PA) in northern Italy, which emerged around 43,000–42,000 cal BP (Frouin et al., 2022; Higham et al., 2009). Consequently, these two technocomplexes occupied adjacent regions until the PA eventually supplanted the Uluzzian, likely through processes of population turnover and/or cultural assimilation—mechanisms that remain poorly understood by geneticists and archaeologists (Higham et al., 2024). The high frequency of bipolar technology on anvil observed in the PA of southern Italy may reflect such a process of assimilation, although further data are needed to thoroughly investigate this hypothesis (Marciani et al., 2020).

The PA is part of the broader Aurignacian technocomplex, which spans a large geographic area across the northern Mediterranean Basin, Atlantic, and Continental Europe (Bar-Yosef and Zilhão, 2006; Le Brun-Ricalens and Bordes, 2007). The Aurignacian technocomplex persisted for approximately eight millennia (Wood et al., 2014) and, due to its marked diachronic variability, is divided into several phases, with the PA representing the earliest phase in southern and western Europe, both stratigraphically and chronometrically (Banks et al., 2013a; Bon et al., 2010).

In terms of stone tool production, the most significant difference between the Uluzzian and the PA is the use of direct freehand percussion to obtain straight and regular bladelets from volumetric cores with plain striking platforms (Bon and Bodu, 2002; Falcucci et al., 2017). These bladelets were often modified through marginal retouching and are frequently classified as Dufour bladelets (Demars and Laurent, 1992; Falcucci et al., 2018; Falcucci and Peresani, 2022). The production of larger artifacts, such as blades and flakes, was typically integrated into the bladelet reduction sequence, as these blanks are often associated with the initialization and maintenance operations performed on bladelet cores (Anderson et al., 2015; Falcucci et al., 2022, 2024a; Lombao et al., 2023). PA foragers relied on high-quality raw materials, and there is evidence of long-distance transport of nodules and finished tools at certain sites (e.g., Falcucci et al., 2025a; Grimaldi et al., 2014; Porraz et al., 2010; Riel-Salvatore and Negrino, 2018b).

The subtle distinction and overlap in the production of blades and bladelets have enabled researchers to identify a marked difference between the PA and the subsequent Early Aurignacian (EA) phase (Le Brun-Ricalens et al., 2005). The EA is characterized by the systematic use of carinated technology to produce miniaturized bladelets (Dinnis et al., 2019; Teyssandier, 2023). Additionally, a key aspect of the EA is the use of antler as a raw material for crafting mechanically delivered projectiles (Tejero and Grimaldi, 2015). In particular, the split-based point (SBP) is often regarded as a hallmark of the EA (Banks et al., 2013a; Tejero, 2014; Teyssandier, 2023).

In both the PA and EA of Italy, symbolic behavior is evidenced by the use of marine and freshwater shells (Stiner, 1999; Vanhaeren and d'Errico, 2006). Notably, some evidence for figurative representations exists at Grotta di Fumane, where ochre-painted stones, found in the upper Aurignacian sequence, depict zoomorphic and anthropomorphic figures (Broglio and Dalmeri, 2005; Sigari et al., 2022). At certain sites, personal ornaments crafted from materials other than shells—specifically hard animal tissues (such as bone and tooth) and soapstone—have also been discovered (Blanc and Segre, 1953; Broglio and Dalmeri, 2005; Negrino and Riel-Salvatore, 2018; Tejero and Grimaldi, 2015). These materials are more frequently found in the EA, whereas they occur only sporadically in the PA (Tejero and Grimaldi, 2015).

In recent years, several studies at pivotal sites have investigated the intricate processes that led to the development of the Aurignacian across Italy. These sites are not only significant for the regional landscape but also facilitate discussions about broader scenarios. Notably, the most important PA assemblage in southern Italy was discovered in layer rsa' at Grotta di Castelcivita. This site features a high-resolution stratigraphic sequence that includes the Mousterian and Uluzzian layers, all sealed by the Campanian Ignimbrite (CI) eruption around 40,000 cal BP (Gambassini, 1997; Giaccio et al., 2017). Recent reassessments of the Castelcivita sequence have revealed that the PA is succeeded by two EA assemblages (i.e., layers *gic* and *ars*), characterized by a marked increase in the use of carinated technology and the modification of miniaturized bladelets through direct, often bilateral retouching (Falcucci et al., 2024a). These findings challenge previous assumptions regarding the impact of the CI super-eruption and the contemporaneous Heinrich Stadial 4 (HS4) cooling event on the development of the Aurignacian in Europe (Banks et al., 2013a; Giaccio et al., 2017). In fact, local paleoenvironmental data indicates that the first EA layer was characterized by a humid, cold-temperate environment (Falcucci et al., 2024a).

The identification of an early PA to EA shift at Castelcivita is significant, as it was previously believed that the PA persisted longer in Italy than elsewhere in Europe, based on data from Bombrini and Fumane (Falcucci et al., 2020; Riel-Salvatore and Negrino, 2018a). However, revisions of the lithic assemblage integrity at Fumane, along with renewed technological studies of the Aurignacian industries, have challenged this reconstruction, identifying a PA–EA transition at the stratigraphic boundary between layers A2–A1 and D3b alpha (Falcucci et al., 2024b). Layer D3b alpha formed during HS4 (Higham et al., 2009; Marín-Arroyo et al., 2023) and likely records a short-term EA occupation of the site. Similarly, Falcucci et al. (2025a) identified, for the first time, an EA assemblage from layer A0 at Bombrini, which overlies the PA layer A1.

These new assessments align the development of the Italian Aurignacian with the broader European context while highlighting distinct regional features. While the wealth of data on the Italian Aurignacian is primarily associated with the PA, the EA is also documented at stratified sites such as Grotta del Fossellone (Blanc and Segre, 1953; Degano et al., 2019) and Riparo Mochi (Douka et al., 2012; Laplace, 1977). The lithic assemblages from Castelcivita and Fumane have been described using a technological approach, whereas the EA of Fossellone has only been partially analyzed (Degano et al., 2019), and the EA at Mochi was primarily examined using the analytical typology by Laplace (1977). However, at Mochi, a detailed study of bone tools—particularly antler implements—was conducted by Tejero and Grimaldi (2015). Notably, the exploitation of antler resources in the Aurignacian of southern Italy remains undescribed (Arrighi et al., 2020c).

Despite the new data regarding the PA and EA at Castelcivita, the sealing of the sequence by the CI tephra limits investigations into the development of the Aurignacian post-CI and during HS4 in southern Italy. Grotta della Cala (hereafter La Cala) presents an excellent opportunity to extend this chronological framework. Located 57 km as the crow flies south from Castelcivita, new radiometric data place its Aurignacian sequence within HS4 and the onset of Greenland Interstadial 8 (GI8) (Higham et al., 2024), thereby providing essential chronological context for addressing this research gap. Historically, La Cala was assigned to the PA based on a limited number of bladelets with marginal retouching (Benini et al., 1997; Marciani et al., 2020; Palma di Cesnola, 2001). However, the new chronological evidence highlights the need for a comprehensive re-evaluation of the Aurignacian sequence at this site.

This study aims to re-examine the archaeological data from La Cala, derived from both past and ongoing excavations, to track the development of the Aurignacian in southern Italy after 40,000 cal BP. By revisiting various archaeological evidence—including lithic and osseous technologies utilizing updated methodologies, as well as marine shells—we demonstrate that the entire Aurignacian deposit at La Cala can be attributed to the EA. Notably, we describe the southernmost SBPs in Europe, providing additional data that support the lithic findings and reveal previously unknown internal chronological and regional variability within the EA. This updated framework positions La Cala's EA within the broader Italian context. To achieve this, we employ Kernel Density Estimates (KDE) to discuss the archaeological evidence within the revised chronometric and stratigraphic reconstructions across Italian sites. Ultimately, this study addresses the cultural trajectories of the Upper Paleolithic and offers new insights into the adaptation and resilience of *Homo sapiens* groups in southern Italy. The findings

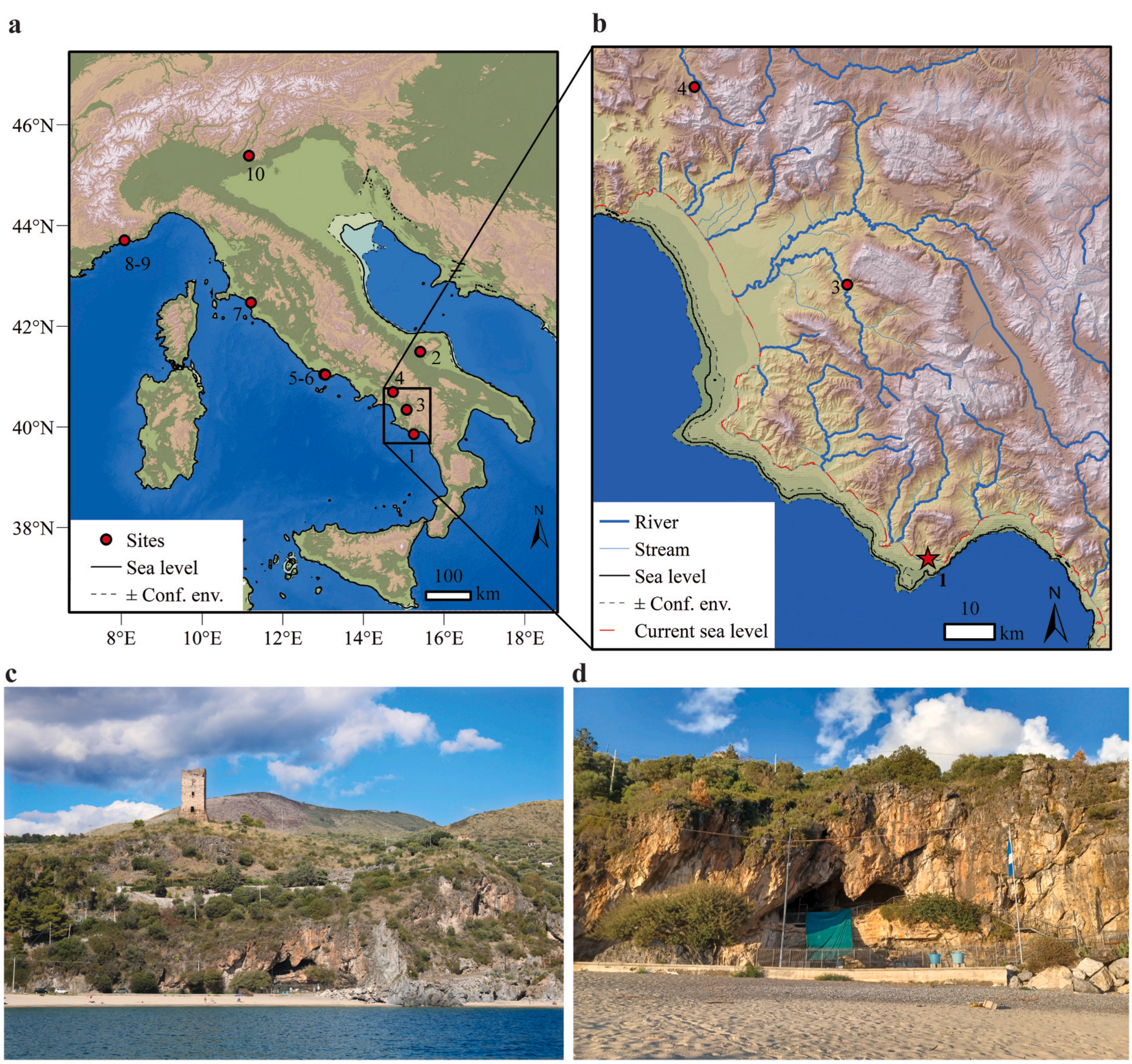

Fig. 1. Geographic location of Grotta della Cala and other Aurignacian sites mentioned in the text (a), alongside a view of the Cilento region that illustrates the topographical context of Grotta della Cala (b). Reported sites include: 1) Grotta della Cala, 2) Grotta Paglicci, 3) Grotta di Castelcivita, 4) Serino, 5–6) Grotta del Fossellone and Grotta Barbara, 7) Grotta La Fabbrica, 8–9) Riparo Mochi and Riparo Bombrini, and 10) Grotta di Fumane. The maps depict paleo-geographic reconstructions of Italy and the Cilento region, considering mean sea-level estimations with associated confidence intervals of approximately −62 ± 13 m above the current sea level at about 38,000 BP. (Map by V. Spagnolo). c) View of Grotta della Cala from the sea and d) close-up view of its entrance (Photos by A. Moroni).

significantly enhance our understanding of regional and chronological variability within the Aurignacian, contributing to broader discussions on human behavioral evolution during this period.

2. The site of Grotta della Cala within its regional setting

La Cala (Camerota, Salerno, Cilento, 40.00108243N, 015.38095416E, 3 m a.s.l.) is located on the present-day coastline, at the base of a hilly-mountainous landscape characterized by short tablelands ranging from 250 to 500 meters above sea level (Fig. 1). The cave, which opens in dolomitic limestone, consists of two main chambers connected by a narrow bottleneck formed by a large stalagmite (Moroni et al., 2016). Systematic excavations at the site began in 1966 under the direction of A. Palma di Cesnola from the University of Siena (1966–1974). Subsequent excavations were conducted by P. Gambassini (1971–2006) and A. Moroni (2014–ongoing), also from the same university.

The Pleistocene deposits at the site have been investigated in two primary areas (Fig. S1). The initial excavations led by Palma di Cesnola focused on the internal sequence, located in the middle part of the cave. The trench excavated during these early years was approximately 3 m deep and covered an area of about 12 m^2. In this internal sequence, the Upper Paleolithic begins with the evolved Gravettian (layer Q), which rests on a thick flowstone layer (designated as β). Flowstone β is divided

Fig. 2. a) Stratigraphic profile of the Mousterian to Early Gravettian sequence in the Atrium Series of the cave, highlighting the main cultural boundaries (MU = Mousterian, UL = Uluzzian, AU = Aurignacian, GB = Gravettian base, namely the Early Gravettian). The sub-layers corresponding to the Aurignacian deposit (AU10 to AU13) and the locations of the primary living floors related to AU10, AU12, and AU13 are indicated by red arrows on the right side of the stratigraphy. The sedimentological difference between the Uluzzian (UL), the underlying Mousterian (MU), and the overlying Aurignacian (AU) is clearly visible. b) Photomosaic of a portion of the living floor, still in situ, located at the top of the Aurignacian sequence (AU10, uncovered in 2016). c) Panoramic and vertical views of a detail from the bone bed in AU12. (Photos a and c from P. Gambassini's archive; photo b by S. Ricci). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

into two main banks: β II, the lower, thicker, and more compact layer, which serves as a barrier to the Middle Paleolithic deposits, and β I, the upper, thinner layer. In some locations, pockets of brown sediment containing Gravettian lithics are found between these layers (Fig. S1). Above the Gravettian, the sequence includes Epigravettian deposits, spanning from the early to the final phases (Martini et al., 2018; Rossini et al., 2025). These are overlain by flowstone α, followed by layers from the Mesolithic, Neolithic, and Metal Ages, documenting a long-lasting human presence in the cave (Martini et al., 2018; Moroni et al., 2016).

In the 1970s, Gambassini opened a new trench of approximately 28 m^2 near the cave entrance, known as the Atrium Series, where he uncovered an archaeological deposit about 1 m thick. This deposit contained evidence of several technocomplexes, including the Early Gravettian (EG), Aurignacian (AU10–AU13), Uluzzian (UL14), and Mousterian (MU15). According to Benini et al. (1997), the Uluzzian layer is thought to correspond to the formation of flowstone β II in the Internal Series (see Fig. S1). Below the Uluzzian layer, the Mousterian (MU) deposit, represented by layers R and S in the Internal Series (where it is about 25 cm thick), is only 10 cm thick. Both the Internal Series and the Atrium Series rest on a strongly cemented marine conglomerate, which is hypothesized to belong to Marine Isotope Stage 5e (MIS 5e).

In the Atrium Series, the Upper Paleolithic sequence begins with the Uluzzian layer (UL14), a 15 cm thick cemented breccia. The EA overlays the Uluzzian deposit, with no intervening PA layers, after a geological gap marked by a clear change in sedimentation. This gap also corresponds with the absence of sediments accumulated during a time-equivalent interval of PA occupations in nearby areas of Campania, such as Castelcivita and Serino (Accorsi et al., 1979; Falcucci et al., 2024a; Higham et al., 2024; Wood et al., 2012).

From a lithological perspective, the EA layer, approximately 40 cm thick, is primarily composed of sand, debris, and thin flowstone (Fig. 2a). Despite its relative homogeneity, natural discontinuities—such as changes in compactness, texture, and color—and the presence of specific features (like bone beds and fireplaces) have been recognized during excavation (Benini et al., 1997). Notably, living floors with dense accumulations of bones were identified in sub-layers AU10 (Fig. 2b and Fig. S2) and AU12 (Fig. 2c). Additionally, a non-structured hearth was found in AU13 (Fig. 3).

The Aurignacian sequence is sealed by a flowstone sub-layer (AU10), which creates a distinct boundary with the subsequent Early Gravettian deposit. This cemented surface features circular pools of varying dimensions, formed by prolonged dripping from the cave vault, indicating a temporal gap and a lack of clastic sedimentation prior to the formation of the Gravettian deposit (see Fig. S2–S3). The last Aurignacian occupation is evidenced by materials directly cemented at the top of this sub-layer, mainly concentrated in a strip of squares (i.e., B6–B10) along the western wall of the cave. This suggests a specific human activity, a hypothesis supported by geological data exposed below, particularly the sub-horizontal bedding of the EA layer (Fig. 4A). It follows that the possibility of local accumulation of findings due to gravity-driven processes toward a cave sector can be excluded. Further taphonomic analyses will help clarify the processes responsible for this peculiar accumulation (e.g., evaluating the presence and intensity of possible carnivore activity versus human activity).

The entire stratigraphic sequence exposed at La Cala has been investigated from a sedimentological and allostratigraphic perspective by Martini et al. (2018), to which the reader is referred for further detail. The deposits pertaining to the EA belong to the oldest allostratigraphic unit recognized by Martini et al. (2018). From a sedimentological point of view, this unit can be subdivided into nine beds (Fig. 4). Most of these beds were formed by: i) dominant rockfall processes (i.e., structureless or faintly stratified beds dominated by allochthonous debris derived from the mechanical disintegration of the cave vault); and ii) degassing of vadose and carbonate-rich percolation waters, which formed cm-thick flowstone layers showing pervasive plane-parallel lamination. These layers sometimes contain siliciclastic materials, such as granules, small clasts, and debris.

Only one thin bed (maximum thickness 6 cm; see sedimentary log in Fig. 4B) shows different features, such as a slight erosional base and internal low-angle cross-lamination, suggesting deposition by flowing waters in a stream-like setting. However, the low depth/width ratio of the channel-stream fill reported for this bed by Martini et al. (2018)

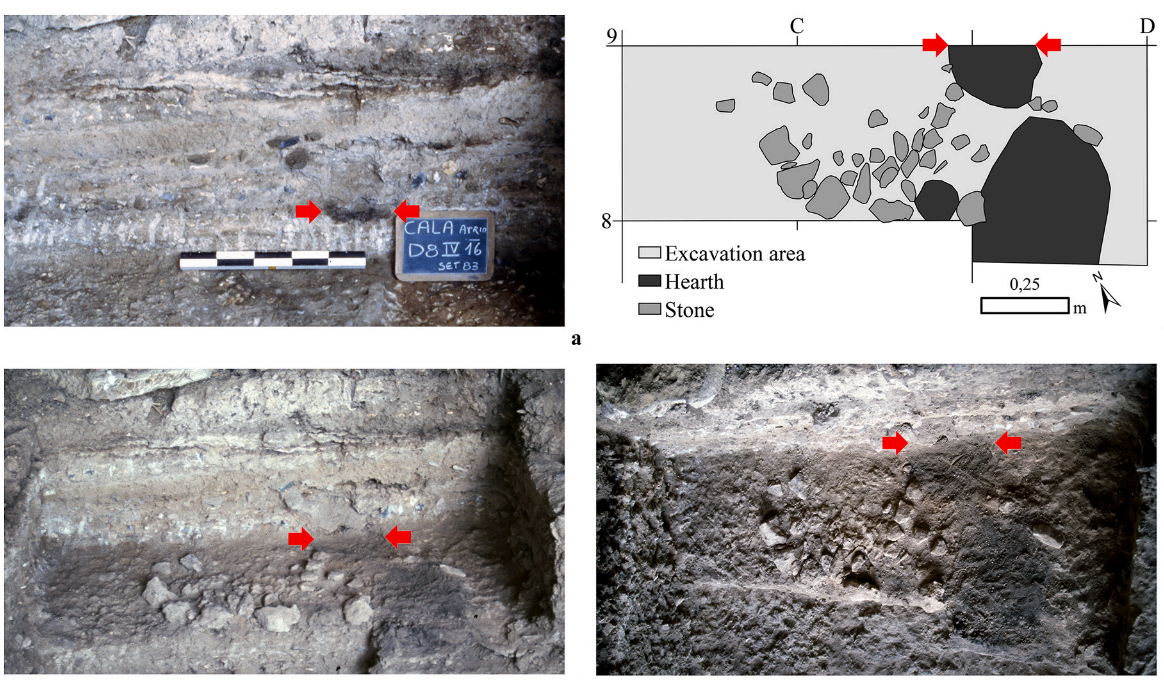

Fig. 3. Living floor of AU13, featuring the hearth (indicated by red arrows). a) Location of the living floor in the exposed stratigraphic section from 1983; b) detailed plan of the hearth and surrounding stones; c) panoramic photograph; d) vertical photograph. (Drawing by V. Spagnolo; photos from P. Gambassini's archive). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

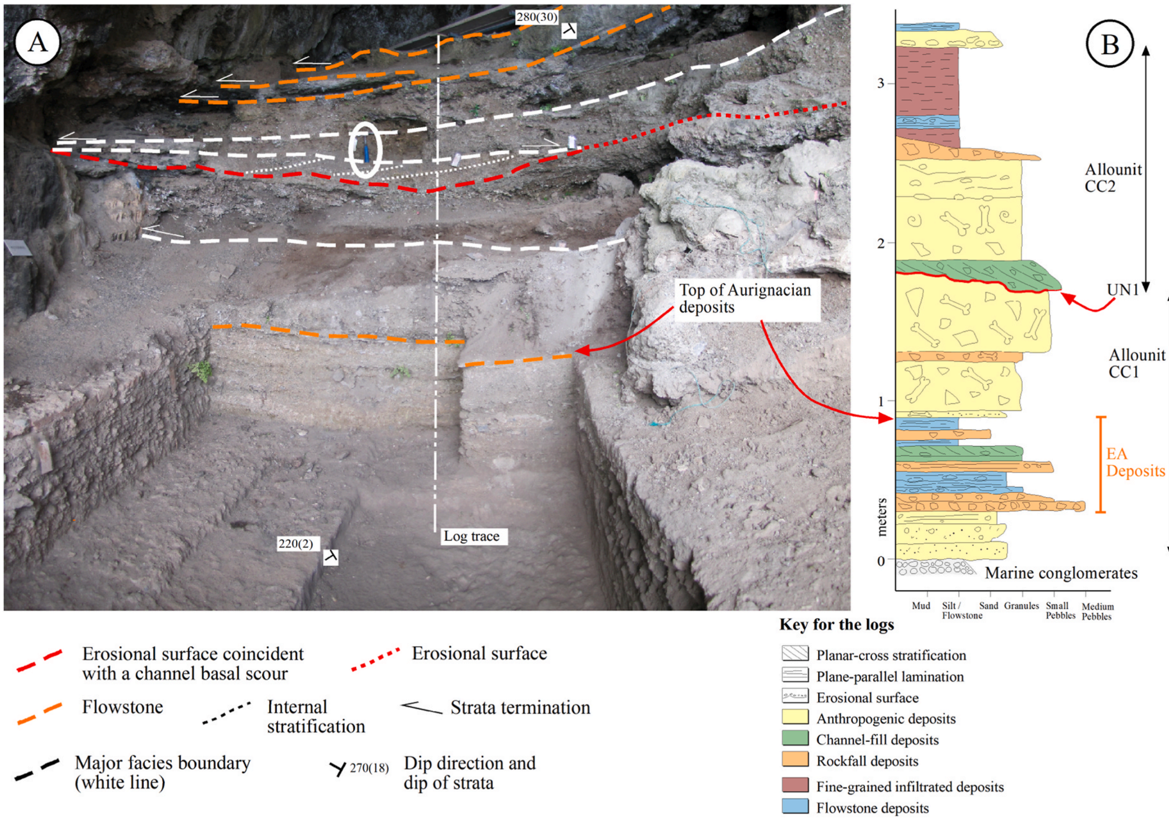

Fig. 4. (A) Panoramic view of the Atrium Series. The hammer for scale is approximately 28 cm long, and the exposed succession is about 3.5 m thick. (B) Sedimentary log of the stratigraphic succession (modified from Martini et al., 2018). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

suggests poorly confined flows with limited erosional power. The overall EA sequence shows no evidence of bioturbation or post-depositional alteration. Moreover, the preserved sedimentary structures, the occurrence of flowstone, and the cementation of most of the excavated beds exclude post-depositional reworking of the succession.

Regarding the absence of PA deposits, the sedimentological data presented by Martini et al. (2018) provide provide robust evidence to exclude the erosion of previously deposited sediments. Even if the lowermost Aurignacian sub-layer corresponds to a “brecciated flowstone,” indicating sediment accumulation in settings characterized by flowing waters, the hydrodynamic conditions associated with the deposition of such materials are generally not energetic enough to erode previously deposited coarse-grained sediments. This is corroborated by the lack of an erosional surface between the Uluzzian and EA deposits (see Fig. 4). Conversely, the low sediment accumulation rates in the Atrium Series suggest that deposition during the PA time interval cannot be ruled out, nor can it be excluded that thin sedimentation occurred and was later bioturbated by anthropogenic activities during the EA occupations (see Martini et al., 2021 as an example for this occurrence).

Initially, the dating of the anthropogenic sequence at La Cala, which spans approximately 80,000 years within about 3 m of sediment and covers periods from the Middle Paleolithic to the Bronze Age, relied on a series of radiocarbon determinations performed on charcoal and burned bones. Although these dates were obtained using techniques now considered outdated, the chronology of the upper part of the deposit (i.e., from the evolved Gravettian to the Copper Age) remains consistent with the stratigraphic succession and the cultural attribution of the layers (Azzi et al., 1973; Azzi and Gulisano, 1979). The dates for the Uluzzian and EA layers, however, were more problematic and unreliable, appearing too young compared to other deposits associated with these cultural units across Italy (Azzi et al., 1977; Benini et al., 1997; Hedges et al., 1998).

Recently, Higham et al. (2024) conducted a new dating program utilizing radiocarbon and optically stimulated luminescence (OSL) techniques, resulting in updated chronological boundaries. The transition between the Uluzzian and Aurignacian at La Cala is now estimated to occur between 40,097 and 37,761 cal BP (68.3 % probability) or 42,580 and 37,200 cal BP (95.4 % probability). The end of the Aurignacian is modeled to be between 38,747 and 36,197 cal BP (68.3 % probability) or 39,226 and 30,554 cal BP (95.4 % probability). Overall, the available OSL date from AU12 (X7042, 38,390–34,682 cal BP at 68.3 % probability) and the radiocarbon date from AU10 (OxA-35601, 38,840–37,637 cal BP at 68.3 % probability) suggest that the Aurignacian sequence was deposited after 40,000 years ago.

The study conducted by Benini et al. (1997) on faunal remains from Uluzzian and Aurignacian layers indicates that most of the bone remains recovered are linked to human activity at the site, with minimal evidence of carnivore gnawing marks and an absence of coprolites. Additionally, carnivores’ deciduous teeth are absent, ruling out the possibility of denning activities. Carnivores are more abundant in the Uluzzian layer. Among the fauna in AU13–AU10, red deer (*Cervus elaphus*) is the most common species, representing close to or over half of all identified ungulate remains, which is significantly higher than the frequency in the Uluzzian layer (16.7 % of identified remains), where fallow deer (*Dama dama*) is the dominant taxon (Benini et al., 1997). Other abundant species in AU13–AU10 include fallow deer (*Dama dama*) and wild boar (*Sus scrofa*), while wild horse (*Equus ferus*) is relatively rare throughout the sequence (Table 1). Notably, the abundance of cervids reflects a continuing trend observed in the last glacial cycles in this area of the Italian peninsula (Sala, 1983) and aligns with palaeobotanical data (Di Pasquale et al., 2020). In addition, zooarchaeological data from AU13–AU10 aligns with the pronounced

Table 1
Ungulates across AU13–AU10: NISP (Number of Identified Species) and percentages.

	AU10		AU11		AU12		AU13	
	NISP	%	NISP	%	NISP	%	NISP	%
Equus ferus	–	–	4	1.8	10	2.3	5	2.2
Sus scrofa	–	–	28	12.8	52	12.1	10	4.3
Bos primigenius	–	–	2	0.9	8	1.9	7	3.0
Capra ibex	–	–	15	6.8	14	3.3	12	5.2
Rupicapra cfr. *pyrenaica*	–	–	1	0.5	2	0.5	4	1.7
Caprinae sp.	–	–	–	–	1	0.2	–	–
Cervus elaphus	6	–	128	58.4	213	49.8	132	57.4
Dama dama	1	–	17	7.8	62	14.5	42	18.3
Capreolus capreolus	2	–	15	6.8	44	10.3	8	3.5
Cervidae sp.	–	–	9	4.1	22	5.1	10	4.3
Total	9		219		428		230	

regionalization of the Italian Peninsula during the Upper Paleolithic. This is supported by studies on ungulate and micromammal remains in central-southern Italy. The Tyrrhenian side predominantly featured woodland-adapted species, whereas arid conditions generally prevailed in the Adriatic regions. Faunal assemblages there exhibited lower biodiversity and were dominated by a few species (Boschin et al., 2018).

3. Materials and methods

3.1. Excavation methodology

Both past and present excavations of the Atrium Series at La Cala adhered strictly to the stratigraphic succession. A 1 × 1 m grid system was employed in the excavation area, further subdivided into 50 × 50 cm sectors. As previously mentioned, four sub-layers were recognized in the Aurignacian deposit based on lithostratigraphic characteristics and the presence of natural discontinuities: AU13, AU12, AU11, and AU10. To improve the vertical resolution of the materials, these sub-layers were further subdivided into 5 cm spits. Features related to human activity were recorded separately. Finds larger than 1 cm were collected by recording their 3D coordinates, and sediments were systematically dry- and wet-sieved using 1 mm meshes to prevent the loss of small items. Throughout the excavations, all surfaces and notable features were documented through notes, photographs, graphic reliefs, and, in the most recent fieldwork, photogrammetry. For the purposes of this study, we used the sub-layers as reference units to investigate the site diachronically, starting with the earliest sub-layer (AU13) and progressing to the uppermost (AU10). All materials analyzed in this paper were excavated from an area of approximately 17 m^2 by P. Gambassini between 1979 and 1989, and later by A. Moroni starting in 2014 (Fig. S4–S5).

3.2. The material selection

Lithics. During the initial sorting of lithic materials, it became apparent that all assemblages demonstrated a notable reliance on carinated technology for bladelet production. To thoroughly investigate this critical aspect within the Aurignacian framework, we analyzed all tools, cores, complete blades, and bladelets, as well as all blanks involved in the initialization and maintenance of laminar production (Table 2). In terms of assemblage size across the different sub-layers, the lowermost AU13 yielded the most abundant lithic collection, while the uppermost AU10 contained a significantly reduced number of lithics. These assemblages were initially studied by Benini et al. (1997), who primarily applied a typological approach. In the literature, these assemblages are often assigned to the PA (Marciani et al., 2020), following the initial attribution by Benini et al. (1997), largely based on the presence of a limited number of bladelets with marginal retouching, similar to those

Table 2
Quantification of the studied assemblages categorized by lithic classes and their respective sub-layers of provenance. The category "core-tool" includes artifacts involved in the production of bladelets (e.g., carinated endscrapers and burin cores) that can also be classified as tools from a typological perspective. These artifacts have been kept separate from the core list to facilitate inter-site comparisons. Percentages are provided in brackets.

	Core	Core-Tool	Blank	Tool	Pebble	Total
AU10	13 (8.7 %)	9 (6.0 %)	92 (61.7 %)	34 (22.8 %)	1 (0.7 %)	149
AU11	29 (9.5 %)	32 (10.5 %)	173 (56.5 %)	71 (23.2 %)	1 (0.3 %)	306
AU12	55 (11.3 %)	48 (9.9 %)	275 (56.6 %)	107 (22.0 %)	1 (0.2 %)	486
AU13	61 (10.4 %)	37 (6.3 %)	418 (71.6 %)	68 (11.6 %)	–	584
Total	158 (10.4 %)	126 (8.3 %)	958 (62.8 %)	280 (18.4 %)	3 (0.2 %)	1525

recovered at Castelcivita and nearby Serino.

Osseous Artifacts. We analyzed all artifacts categorized as osseous tools recovered from the Aurignacian (n = 4). One object, reported in the review work by Arrighi et al. (2020c), was excluded from the analysis as it was determined to be an unworked incisor root from a medium-sized mammal (Fig. S6). This finding is consistent with Benini et al. (1997), who reported a total of three osseous tools from AU12 (n = 2) and AU13 (n = 1). A comprehensive analysis of faunal materials from the ongoing excavations is still pending to identify additional tools or other components of bone technology, such as by-products, which were beyond the scope of the current study. In this regard, it is important to note that, although numerous red deer remains are primarily represented by skull and limb elements, only one antler fragment was recovered in the previous excavations (Table 3). This skeletal part is absent among the elements of the other two identified cervid species, *Dama dama* and *Capreolus capreolus* (Benini et al., 1997). Of the forty-one specimens related to the Cervidae family, mainly represented by tooth fragments and metapodial shaft portions, ten antler remains have been recorded. Most of these are small apex fragments (n = 7)

Table 3
Cervids: skeletal elements identified in AU13–AU10. Modified after Benini et al. (1997).

	Cervus elaphus	*Dama dama*	*Capreolus capreolus*
Antler	1	–	–
Maxilla	17	3	2
Upper teeth	60	15	6
Mandible	42	7	6
Lower teeth	73	18	8
Unidentified teeth	7	1	11
Vertebrae	2	–	–
Scapula	1	–	1
Humerus	9	–	1
Radius	12	1	1
Ulna	6	–	3
Carpals	15	6	6
Metacarpals	38	7	–
Pelvis	1	–	–
Femur	2	2	–
Patella	1	–	1
Tibiae	5	4	–
Malleoular	3	1	–
Tarsals	14	12	4
Metatarsals	78	24	7
Metapodials	24	2	10
Sesamoids	9	6	1
Phalanx I	29	6	–
Phalanx II	21	6	–
Phalanx III	9	1	1
Total	479	122	69

without signs of anthropic modification, according to Benini (1995). Consequently, it is not yet possible to determine if antler working occurred in situ.

Shells. We re-evaluated the marine malacological assemblage first described by C. Fiocchi in her PhD thesis (Fiocchi, 1998), employing a taxonomic approach and documenting anthropic perforations. Additionally, we incorporated new data on malacology gathered during ongoing archaeological investigations, primarily from AU10. Terrestrial mollusks were only slightly represented and mostly associated with post-depositional processes; therefore, they were not included in this study. The total number of remains counted in the Aurignacian deposit amounts to 556 items.

3.3. Lithic analysis

We conducted a detailed analysis of the lithic assemblages using various methodologies, following the analytical approach developed for the analysis of the Aurignacian sequence at Grotta di Castelcivita (Falcucci et al., 2024a). By combining reduction sequence analysis (Conard and Adler, 1997; Inizan et al., 1995) with attribute analysis (Andrefsky, 1998; Odell, 2004), we investigated the lithic production at the site, with a particular focus on bladelet technologies, which are crucial for understanding the development of the Aurignacian (Dinnis et al., 2019). A detailed description of the lithic technological analysis, along with relevant references, is provided in Supplementary Material (SM) Note 1.

We 3D scanned a large number of artifacts (n = 420) using an Artec Space Spider (Artec Inc., Luxembourg) following the protocol described by Göldner et al. (2022). Most of the scans are of cores or core-tools (n = 252). The goal of the scanning was to extract quantitative data for technological analysis and to create an extensive open-access repository of the Aurignacian lithics from La Cala. This repository is part of the Open Aurignacian Project (Falcucci et al., 2025b) and available for download from Zenodo (Falcucci and Moroni, 2025; https://doi.org/10.5281/zenodo.14165189). Using the 3D meshes, we calculated the volume of all scanned artifacts using the R *rvcg* package (Schlager, 2017). We also imported the scans into Artifact3-D (Grosman et al., 2022) to export the views used for all figures of lithic artifacts with the Plate Panel.

Statistical analysis included both univariate and multivariate tests. Metric variability was tested using non-parametric tests such as the Wilcoxon and Kruskal-Wallis tests, with Holm-Bonferroni sequential correction to minimize the risk of Type I errors (Holm, 1979). We applied Multiple Correspondence Analysis (MCA) using the *FactoMineR* and *factoextra* R packages (Lê et al., 2008) to examine interrelated variables associated with the technological and morphometric features of all complete bladelets recovered across the sequence (Cascalheira, 2019; Leplongeon et al., 2020; Scerri et al., 2014). MCA allowed us to reduce the complexity of our data and explore correlations between different variables. K-means clustering algorithms were used to categorize metric and morphological quantitative variables (e.g., blank elongation and robustness), following the approach outlined by Cascalheira (2019) and grouping the values into three categories: low, medium, and high. All categories representing less than 5 % of the variability were grouped into the category “Other”. After performing the MCA, we used the output scores of the first two dimensions to assess differences between AU13–AU10 through an analysis of variance (ANOVA). All analyses were conducted using R (Posit team, 2023; R Core team, 2023), and the scripts have been published in the associated research compendium on Zenodo (Falcucci et al., 2025b).

3.4. Analysis of osseous artifacts

The osseous tools (n = 3) were initially examined with a magnifying glass at 10 × magnification, followed by analysis using a Hirox KH-7700 3D digital microscope with an MX-MACROZ VI lens (10–20 × magnification), provided by the University of Siena. Anthropogenic modifications were documented based on both macro- and microscopic observations, including fresh fractures. These modifications were recorded separately from post-depositional and taphonomic changes, such as chemical etching and discoloration. The break pattern was classified and described according to Pétillon (2006) and Doyon and Knecht (2014). Maximum length, width, and thickness were measured using a digital caliper with a precision of 0.2 mm and a resolution of 0.1 mm.

The raw material (i.e., antler and bone) was determined based on the nature of the cortical area and spongiosa for the two osseous tools from AU12. For the tool from AU13, this approach was non-diagnostic, so X-ray microcomputed tomography (microCT) scans were used to examine the internal microstructure of the material. The microCT scans enabled a comparison with established references of both bone and antler. For this comparison, we used a bone point from the Early Gravettian layer GB1d (Atrium Series) of the same site (Boscato et al., 1997), a red deer antler spearpoint from the Early Epigravettian layer 17D1 of Grotta Paglicci (Rignano Garganico, Apulia) (Borgia et al., 2016), and a modern reference of unworked deer antler from the osteological reference collection at the University of Siena.

All materials included in this analysis were imaged using microCT as part of an independent project involving a larger dataset of osseous points from Upper Paleolithic contexts in southern Italy. These materials are presented here exclusively for the purpose of addressing the material composition of the tool from AU13. MicroCT measurements were performed at the TomoLab station of the Elettra Sincrotrone Trieste in Basovizza, Italy (Mancini et al., 2007) (see SM Note 2 for additional methodological details and results). The morphometric variability of the osseous tools was compared with specimens from across Europe (Doyon, 2017; Kitagawa and Conard, 2020; Tejero, 2014) to support their typological attributions and to highlight similarities in tool morphometry between La Cala and penecontemporaneous Aurignacian sites.

3.5. Analysis of malacological remains

Taxa identification was performed using a LOMO MBC-10 stereomicroscope (8 × –0.6 × magnification). Private malacological collections and several illustrated atlases were consulted for identification (D’Angelo and Gargiullo, 1987; Doneddu and Trainito, 2005). Taxonomic nomenclature was validated against the World Register of Marine Species (WoRMS) online database (www.marinespecies.org). The quantity indices used for shell identification, including NISP (Number of Identified Specimens), MNI (Minimum Number of Individuals), and MNV (Minimum Number of Valves), followed the guidelines outlined by Gutiérrez-Zugasti (2011). For Scaphopoda, the MNI count was based on fragments from the apical portion (Ø < 2 mm).

Anthropogenic modifications on shells were further examined using an Hirox KH-7700 3D digital microscope with an MXG-10C body and OL-140II lenses (140 × – 480 × magnification), provided by the University of Siena. Special attention was given to analyzing perforations on the shells to determine their origin—whether natural, animal-induced (e.g., predatory drilling or natural erosion), or anthropogenic—following the methodology described by Taborin (1993b) and Tátá et al. (2014).

3.6. Chronometric dating and data comparison

To contextualize the results of our study and facilitate comparison with other sites, we incorporated all available radiometric determinations from stratigraphic sequences assigned to the EA across Italy, and compared them with the new age determinations from La Cala by Higham et al. (2024). We selected both radiocarbon dates (from shell and charcoal) and OSL dates. Most of the radiocarbon dates we used from Italian EA sites were obtained with modern pretreatment chemistry. Radiocarbon dates obtained prior to the application of pretreatment chemistry were only included when recent dating programs confirmed their reliability, such as the dates reported by Hedges et al. (1998) from stratigraphic unit G, spits 51–50 at Mochi. Conversely, we excluded dates or stratigraphic sequences when the chronological determination and/or cultural attribution was considered unreliable, based on published literature.

All sediment samples used for OSL dating were collected and processed in recent years. We calibrated all radiocarbon and OSL ages using OxCal v.4.4 software (Bronk Ramsey, 2009; Bronk Ramsey and Lee, 2013) and the INTCAL20 and MARINE20 calibration curves (Heaton et al., 2020; Reimer et al., 2020). For shell dates, we applied an undefined marine reservoir correction value (`Delta_R("Undefined Local Marine", U(-479, 500, 500))` due to assumptions about temporal changes in the reservoir (Higham et al., 2024). Radiocarbon determinations flagged as underestimations were excluded from the analysis.

We used the `R_Date` command for radiocarbon ages and the `Date` command for OSL ages, specifying the measurement year when known (e.g., La Cala, Castelcivita) or the publication year (e.g., Fossellone) when the measurement year was unknown. For OSL determinations, we used random error for calibrating the dates, following the methodology of Higham et al. (2024). Finally, we summarized the available dates and displayed their distribution using a non-parametric KDE, as outlined in Bronk Ramsey (2017), using the `KDE_Plot` function in OxCal. The SM Note 3 contains the OxCal code for the KDE model.

4. Results

4.1. Lithic technology

4.1.1. Raw material selection

The lithic assemblages at Grotta della Cala are primarily composed of chert and radiolarite (Benini et al., 1997). Chert is typically blackish in color, and in some instances, it exhibits poor knapping qualities due to a non-homogeneous internal texture. In contrast, radiolarite exhibits superior knapping properties and is characterized by a wider range of colors. A study on raw material provisioning at the nearby Upper Paleolithic and Mesolithic site of Grotta della Serratura has identified several distinct groups of cherts and radiolarites, with most raw materials sourced from locations within 0–15 km of the site (Martini et al., 2003). These materials are primarily small pebbles, often collected from beaches due to their cortex characteristics. Raw materials from distances of 15–28 km were predominantly sourced from the mouth of the Alento River, while materials collected from beyond 28 km are far less common in the Upper Paleolithic layers.

At La Cala, when sorting tools by raw material type, chert is more numerous in AU10, whereas radiolarite is slightly more attested across the remaining sub-layers, with percentages ranging from approximately 46 %–54 % (Table S1). The frequency of these materials varies among cores. In AU13, laminar cores are predominantly made from chert, while in the other sub-layers, the proportions of chert and radiolarite stabilize (Table S2). In the case of flake and bipolar cores, radiolarite was more frequently used than chert in AU13–AU12 (Table S3), possibly reflecting the intense exploitation of high-quality raw materials (see below). Other raw materials, such as quartzite and siliceous limestone, were rarely utilized.

Examination of visible knapping features, particularly on tested and initial bladelet cores, indicates that most pebbles were split in half using the bipolar technique on anvil, which created a flat striking platform. Many pebbles also show negative percussion bulb marks. Blades were seldom produced at La Cala (see below), and this absence of blade production is likely due to the size and quality of the available raw materials. Blades may have been introduced to the site and discarded after use. Notably, we identified several lithics made from chert not locally available, likely sourced from the Maiolica formation of the Gargano Promontory (Apulia; Fig. 5). While a comprehensive petrological analysis is still pending, this exogenous chert likely originated from an area approximately 200 km from the site, as the crow flies. Among these lithics, a thick-nosed endscraper (Fig. 5a), two carinated endscrapers (Fig. 5c–e), and a heavily retouched blade with several burin spalls detached on both sides (Fig. 5b) are particularly noteworthy.

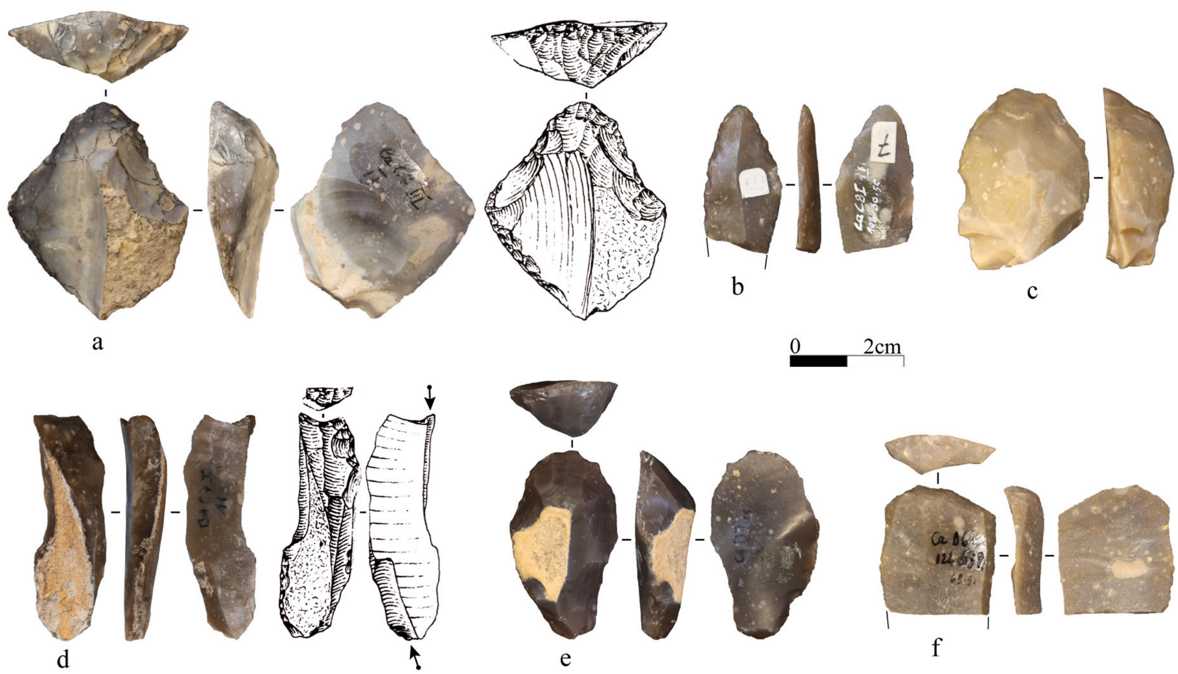

Fig. 5. Selection of tools made from non-local chert (a) Thick-nosed endscraper, (b) blade with scalariform retouch, (c) carinated endscraper, (d) fragmented retouched blade with burin spalls and distal truncation, (e) carinated endscraper with lateral stepped retouch (i.e., Aurignacian retouch), (f) simple. endscraper on a fragmented blade. Figures (a) and (d) are complemented by drawings from Benini et al. (1997). The letters in the figure correspond to the following IDs in both the associated dataset and 3D model repository: a = Ca_119; b = Ca_63; c = Ca_99; d = Ca_370; e = Ca_77; f = Ca_112. (Photos by M. Rossini & A. Falcucci).

4.1.2. Tools

The tools discarded at the site provide valuable insight into the organization of lithic production across the Aurignacian deposit (Table 4). One of the most striking features of the assemblage is the remarkably low number of retouched bladelets (n = 16), with intra-layer percentages ranging from 1.9 % to 5.8 % (Fig. 6). Most of the retouched bladelets were modified with direct marginal retouching, while only three were modified using inverse retouching (Table S4). Notably, one complete bladelet from AU13 closely resembles the micro points well-described in the EA layer (*gic–ars*) at Grotta di Castelcivita (Falcucci et al., 2024a; Gambassini, 1997). This tool measures 14 mm in length and exhibits direct bilateral marginal retouch (Fig. 6a).

Typologically, the most prevalent tool classes at La Cala are endscrapers and retouched flakes (Fig. S7). Retouched flakes outnumber endscrapers only in AU10, although this sub-layer has a relatively small number of tools overall (n = 43). Upon further sorting composite tools, the frequency of endscrapers increases across all assemblages (Table S5). The occurrence of burins (Fig. S7–S8) remains consistently low, with negligible stratigraphic variation. Notably, several blades and flakes exhibit the characteristic Aurignacian retouch, which is stepped, direct, and often quite invasive. This type of retouch is especially common in AU12 (n = 9; 13.4 % of all laterally retouched tools) and AU11 (n = 11; 23.9 % of all laterally retouched tools). AU13 and AU10 feature only a few artifacts modified with this retouch type (two and three, respectively).

Regarding blank selection, tools and core-tools are predominantly made from flakes (Table S6), with flakes consistently accounting for more than 70 % of the assemblages. Blades are also present, though mostly associated with the transport of blanks produced elsewhere, as no cores show clear evidence of blade production. The high prevalence of retouched blades, categorized under the optimal reduction phase, strongly suggests the off-site production of these blanks, particularly when compared with the limited number of blanks from the initialization and maintenance phases (Table S7). This pattern is especially evident in AU12, where sorting according to technological categories shows a distinct concentration of tools on flakes (Table S8).

One of the most noteworthy aspects of the tool assemblage is the overwhelming presence of carinated pieces, primarily endscrapers and *Rabots* (see Figs. 5 and 6), as well as burins (Fig. S8). We interpret all carinated pieces as bladelet cores, given the elongated and regular bladelet negatives visible, along with the very low frequency of other platform cores throughout the sequence. Among the carinated pieces, thick-nosed endscrapers are relatively common (e.g., Figs. 5a and 6l, o). These artifacts are likely associated with the gradual reduction and lateral maintenance of the endscraper front during blank production (Le Brun-Ricalens, 2005). However, further use-wear analysis may reveal a more specific function for these artifacts beyond blank production.

Table 4
General overview of the main tool categories recovered across the studied sequence, with percentages provided in brackets. "Undet." stands for "Undetermined".

	AU10	AU11	AU12	AU13	Total
Blade Aurignacian	–	3 (2.9 %)	3 (1.9 %)	2 (1.9 %)	8 (2.0 %)
Blade pointed	1 (2.3 %)	1 (1.0 %)	1 (0.6 %)	–	3 (0.7 %)
Blade retouched	3 (7.0 %)	6 (5.8 %)	9 (5.8 %)	6 (5.7 %)	24 (5.9 %)
Bladelet retouched	2 (4.7 %)	3 (2.9 %)	9 (5.8 %)	2 (1.9 %)	16 (3.9 %)
Burin	1 (2.3 %)	5 (4.9 %)	5 (3.2 %)	–	11 (2.7 %)
Burin carinated	1 (2.3 %)	–	3 (1.9 %)	4 (3.8 %)	8 (2.0 %)
Burin multiple	–	1 (1.0 %)	1 (0.6 %)	3 (2.9 %)	5 (1.2 %)
Composite tool	7 (16.3 %)	11 (10.7 %)	17 (11.0 %)	11 (10.5 %)	46 (11.3 %)
Endscraper	5 (11.6 %)	10 (9.7 %)	16 (10.3 %)	11 (10.5 %)	42 (10.3 %)
Endscraper carinated	5 (11.6 %)	17 (16.5 %)	26 (16.8 %)	13 (12.4 %)	61 (15.0 %)
Endscraper flat-nosed	–	1 (1.0 %)	5 (3.2 %)	2 (1.9 %)	8 (2.0 %)
Endscraper thick-nosed	1 (2.3 %)	3 (2.9 %)	9 (5.8 %)	5 (4.8 %)	18 (4.4 %)
Flake retouched	13 (30.2 %)	25 (24.3 %)	37 (23.9 %)	24 (22.9 %)	99 (24.4 %)
Rabot	–	6 (5.8 %)	5 (3.2 %)	6 (5.7 %)	17 (4.2 %)
Scaled piece	2 (4.7 %)	5 (4.9 %)	7 (4.5 %)	13 (12.4 %)	27 (6.7 %)
Truncation	–	2 (1.9 %)	–	–	2 (0.5 %)
Undetermined retouched piece	2 (4.7 %)	4 (3.9 %)	2 (1.3 %)	3 (2.9 %)	11 (2.7 %)
Total	43	103	155	105	406

4.1.3. Cores

Most of the bladelet cores discarded at the site can be classified as carinated cores (Table 5), with overall percentages ranging from 58 % in AU10 to 91 % in AU11. Platform cores associated with bladelet production are much less common (Fig. S9).

The technological organization of carinated cores at La Cala is consistent with descriptions from several other Aurignacian sites (e.g., Chiotti, 2000; Falcucci et al., 2024a; Le Brun-Ricalens, 2005; Parow-Souchon and Belfer-Cohen, 2024). The core blank is frequently a flake (Table S9), with the plain striking platform typically positioned on the ventral face (Table S10). The flaking direction is unidirectional, often following a convergent reduction pattern (Table S11). No significant differences are observed across the sub-layers in terms of the volume or length of the flaking surface of carinated cores (Fig. S10), suggesting a stable technological organization of bladelet production across the studied sequence.

When comparing the length of the flaking surface of carinated and platform cores with complete bladelets (Fig. 7a), it becomes evident that most bladelets were produced from carinated cores. In fact, the flaking surfaces of platform cores are significantly longer than those of the carinated pieces. This observation is further supported by the higher number of carinated cores compared to platform cores, as well as by the high frequency of maintenance flakes, which are commonly associated with the maintenance of carinated cores (Chiotti, 2000; Kolobova et al., 2014). A total of 151 flakes can be assigned to this category: 24 in AU10, 33 in AU11, 50 in AU12, and 44 in AU14.

Non-laminar cores are classified in Table 6. The most notable feature is the high frequency of bipolar cores (Fig. S11), which remains fairly stable across the sub-layers, though slightly higher in AU13. Freehand multidirectional and platform cores are less frequent. Also of interest is the presence of parallel and inclined cores, which exhibit centripetal reduction patterns. Bipolar cores typically have two opposed striking platforms (Table S12), one of which often displays the characteristic dihedral morphology (Arrighi et al., 2020b; Peresani et al., 2019b). Overall, bipolar cores have a lower frequency of cortical surface (Table S13) and a smaller volume compared to freehand cores (Fig. S12). This pattern is expected, as the bipolar technique on anvil facilitates further reduction of the cores, which are also more likely to split into several fragments. A few bipolar cores show a combination of bladelet and flake negatives, although the visible removals are irregular (Table S14). These cores likely played a marginal role in bladelet production at the site.

4.1.4. Bladelets

We analyzed all complete bladelets identified in the studied assemblages. Except for AU11, most of the bladelets are made from chert (Table S15), which aligns with the frequency of bladelet cores made from chert. The size of the bladelets is generally small, with median

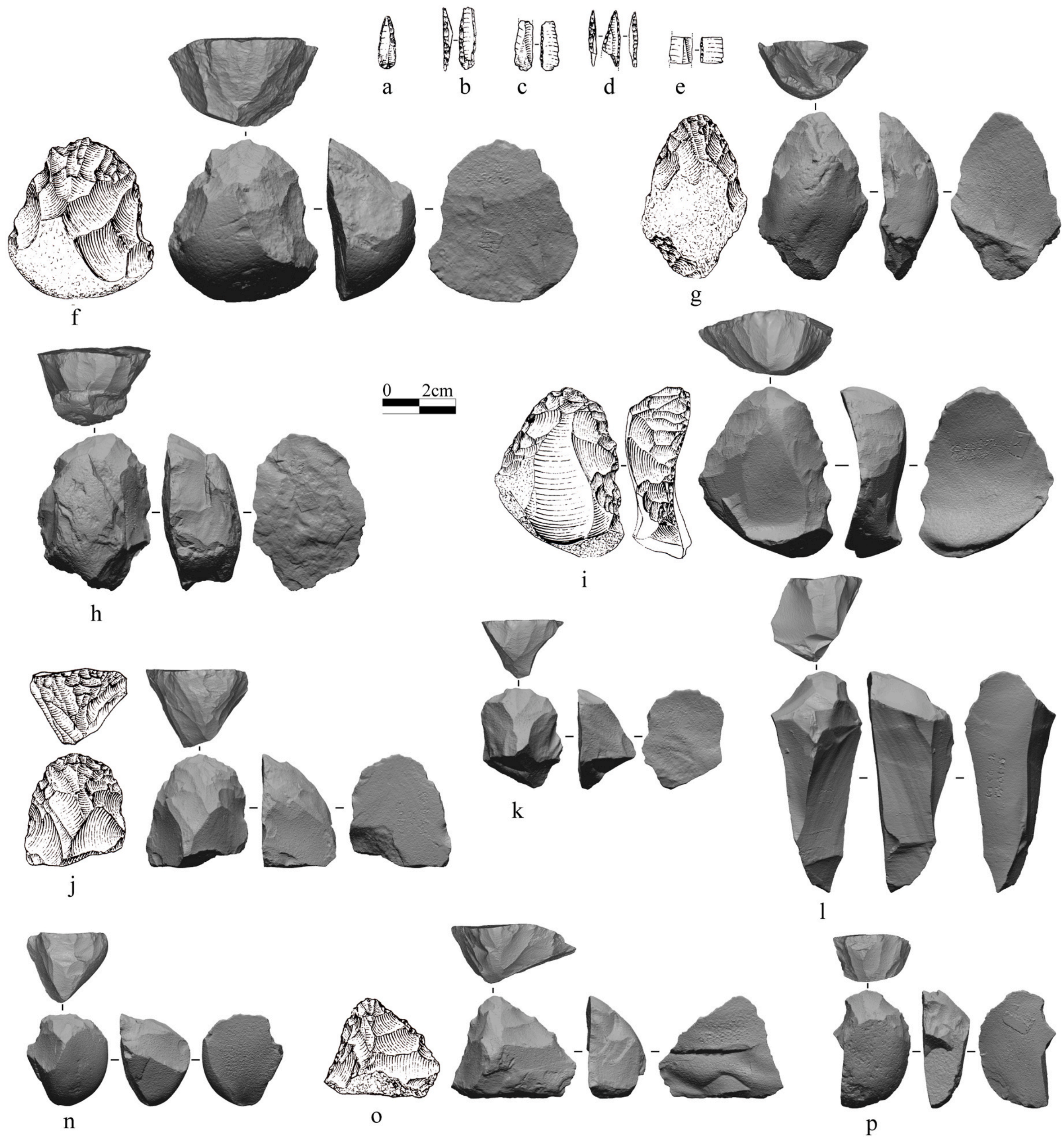

Fig. 6. Retouched bladelets and carinated endscrapers from AU13–AU10 at La Cala. (a, b, and d) are bladelets with direct bilateral retouching; (c and e) are bladelets with unilateral inverse retouching on the right side; (f, j, and n) are *Rabots*; (l and o) are thick-nosed endscrapers; (g, h, i, k, and p) are carinated endscrapers. The figure includes 3D views generated in Artifact3-D and drawings adapted from Benini et al. (1997). Stratigraphic provenience is as follows: (a, c, g, and n) are from AU13; (b, d, e, h, i, l, and o) are from AU12; (f, j, and p) are from AU11; (k) is from AU10. The letters in the figure correspond to the following IDs in both the associated dataset and 3D model repository: a = Ca_1498; b = Ca_1497; c = Ca_1499; d = Ca_1500; e = Ca_1496; f = Ca_127; g = Ca_118; h = Ca_152; i = Ca_120; j = Ca_128; k = Ca_136; l = Ca_1; n = Ca_79; o = Ca_122; p = Ca_47.

length values around or below 15 mm (Table S16). The distribution of length, width, and thickness is very similar across the studied sub-layers (Fig. 7b–d). When sorting bladelets by raw material, those made from chert are slightly shorter and thinner, although the variation is not particularly pronounced (Fig. S13).

The strong similarity between the studied assemblages is also evident in the MCA conducted on the categorical attributes of the bladelets. The first two dimensions of the MCA explain 30 % of the variability of the bladelets (Fig. S14). The first axis (17 % of variation) contrasts bladelets with high elongation and low robustness ratios against those with high robustness and low elongation ratios. The steepness of the cross-section also plays a significant role (Fig. 8a). The second dimension (13 %) contrasts bladelets with unidirectional convergent scar patterns against those with unidirectional parallel scar patterns. Other variables contribute less to the overall variability. The MCA biplot, with bladelets sorted by sub-layer, reveals a strong overlap between the assemblages, as the mean values and confidence ellipses are nearly identical (see Fig. S14e). This indicates that the observed variability cannot be attributed to the stratigraphic position of the recovered artifacts. The results of the multi-comparison bootstrap ANOVA on the first and second components of the MCA further highlight the strong similarity between the assemblages, with loadings for both dimensions close to 0 (Fig. 8b).

Table 5
Core types associated with bladelet production. The classification follows Falcucci and Peresani (2018), which considers the location and orientation of the flaking surface relative to the striking platform(s). The "carinated core" category is classified as "*Rabot*" in the typological list. Percentages are provided in brackets.

	AU10	AU11	AU12	AU13	Total
Initial	1 (8.3 %)	1 (3.0 %)	4 (7.3 %)	6 (13.6 %)	12 (8.3 %)
Carinated endscraper	6 (50.0 %)	25 (75.8 %)	37 (67.3 %)	22 (50.0 %)	90 (62.5 %)
Carinated core	–	5 (15.2 %)	4 (7.3 %)	4 (9.1 %)	13 (9.0 %)
Carinated burin	1 (8.3 %)	–	4 (7.3 %)	4 (9.1 %)	9 (6.2 %)
Burin core	–	1 (3.0 %)	1 (1.8 %)	1 (2.3 %)	3 (2.1 %)
Narrow-sided	1 (8.3 %)	1 (3.0 %)	1 (1.8 %)	2 (4.5 %)	5 (3.5 %)
Semi-circumferential	1 (8.3 %)	–	2 (3.6 %)	2 (4.5 %)	5 (3.5 %)
Wide-faced	–	–	1 (1.8 %)	–	1 (0.7 %)
Multi-platform	1 (8.3 %)	–	1 (1.8 %)	2 (4.5 %)	4 (2.8 %)
Shatter laminar	1 (8.3 %)	–	–	1 (2.3 %)	2 (1.4 %)
Total	12	33	55	44	144

4.2. *Osseous artifacts*

4.2.1. *The split-based points*

Two specimens are attributed to this tool type. The first artifact comes from AU13 and has a maximum length of 31.6 mm, a maximum width of 5.1 mm, and a maximum thickness of 3.1 mm (Fig. 9a). It has an elongated triangular form with an oval cross-section, typical of a pointed tool, specifically an osseous projectile point. Concretions and weathering obscure most of the surface, and no manufacturing traces have been observed. Due to natural taphonomic modifications, the osseous structure – particularly the spongiosa – that distinguishes antlers from bone cannot be observed macro- or microscopically. Therefore, we turned to microCT imaging to study the microstructure of the specimen, which enabled us to attribute it to antler (Fig. S15). The internal canal network of this specimen is similar to that of both modern and

Table 6
Core types associated with flake production, along with bipolar and tested cores. Percentages are provided in brackets.

	AU10	AU11	AU12	AU13	Total
Bipolar	5 (50.0 %)	14 (50.0 %)	27 (56.2 %)	33 (61.1 %)	79 (56.4 %)
Multidirectional	4 (40.0 %)	3 (10.7 %)	10 (20.8 %)	8 (14.8 %)	25 (17.9 %)
Platform flake	–	2 (7.1 %)	4 (8.3 %)	5 (9.3 %)	11 (7.9 %)
Parallel	1 (10.0 %)	4 (14.3 %)	1 (2.1 %)	2 (3.7 %)	8 (5.7 %)
Inclined	–	–	1 (2.1 %)	1 (1.9 %)	2 (1.4 %)
Shatter	–	1 (3.6 %)	1 (2.1 %)	1 (1.9 %)	3 (2.1 %)
Tested	–	4 (14.3 %)	4 (8.3 %)	4 (7.4 %)	12 (8.6 %)
Total	10	28	48	54	140

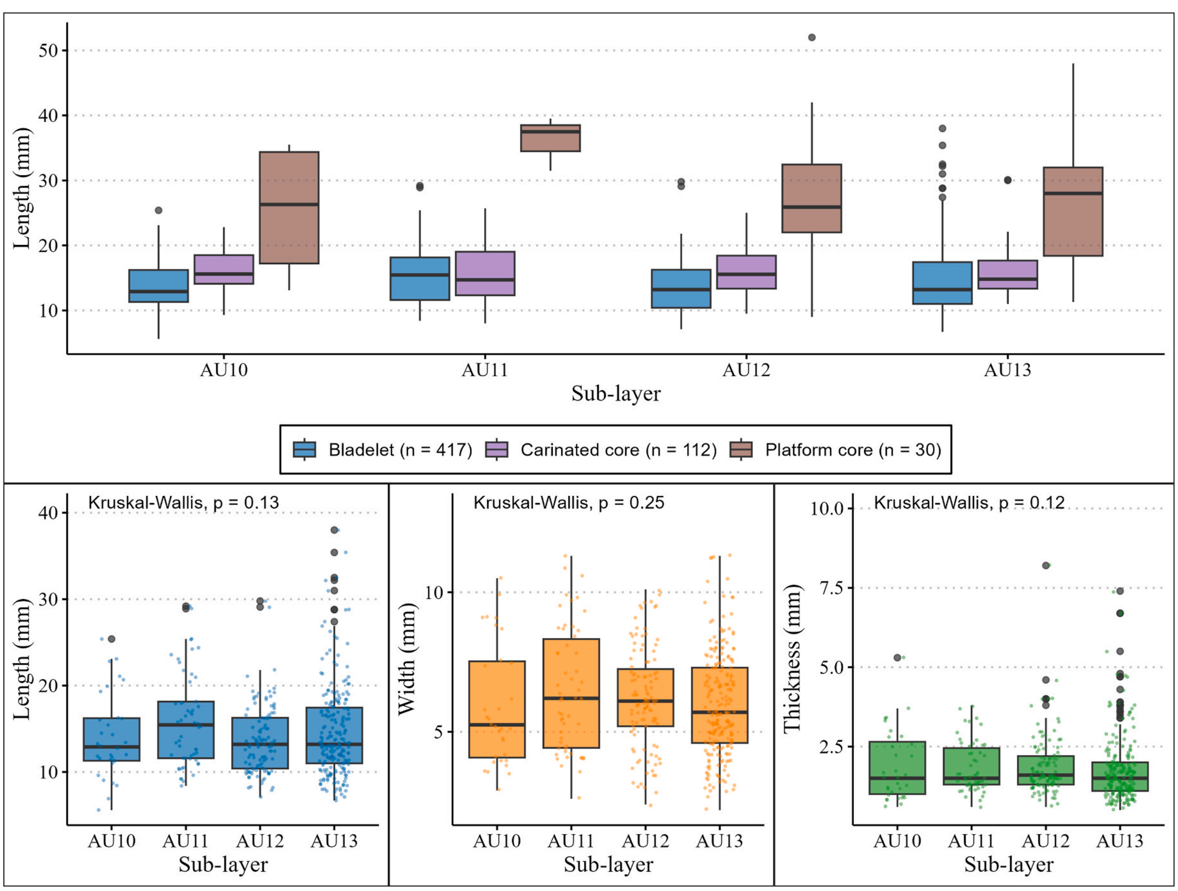

Fig. 7. a) Boxplots showing the distribution of flaking surface lengths (in mm) for carinated cores, platform cores, and complete bladelets from the studied sub-layers. b–d) Boxplots showing the distribution of length (b), width (c), and thickness (d) across the studied sub-layers. Figures b–d include the results of the Kruskal-Wallis tests. All values are in millimeters. Refer to the legend at the bottom of the figure for color-coding. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

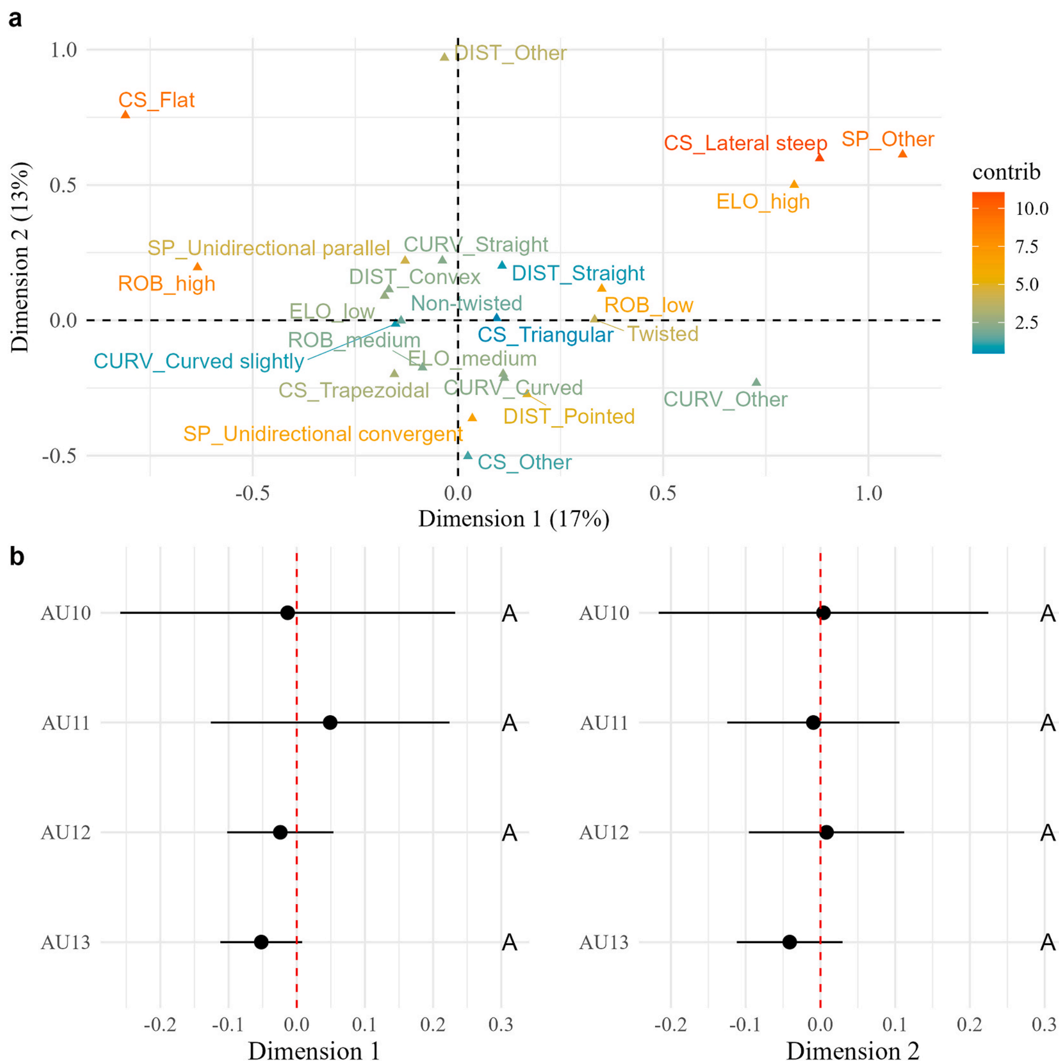

Fig. 8. (**a**) Multiple Correspondence Analysis (MCA) plot (first two dimensions) for the attributes recorded on complete bladelets. The color ramp represents the contribution (%) of variable categories to the definition of the dimensions. (**b**) Results of the multi-comparison bootstrap ANOVA on the first and second dimensions. Error bars represent the 95 % confidence interval from the mean. Contexts sharing the same letter do not show a statistically significant difference (p-value = 0.05). Abbreviations: ELO = Elongation, ROB = Robustness, CURV = Curvature, TORS = Torsion, DIST = Distal end shape, CS = Cross-section shape, SP = Scar pattern. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

archaeological antler in two regions: the distal end and the proximal half (see SM Note 2).

The point exhibits a break at both ends. The distal end (i.e., the tip) shows a tongue fracture with an oblique fracture plane measuring 2 mm in length and 5 mm in width (Fig. 10a). The hafted or proximal half displays a negative scar that extends along the main axis of the point, measuring 10.5 mm in length (Fig. 10b). One plane remains intact, with a small sawtooth-like fracture at the end, while the rest is missing. The fracture pattern on the proximal end suggests that the hafted end had a split running along the entire width of the base, allowing force, likely from a thrusting motion, to detach one half of the split (or wing). Based on the break morphology at the hafted end, we deduce that this artifact is a SBP, which, while small in size, is relatively complete.

The second SBP comes from AU12 and measures 24.0 × 6.9 × 4.7 mm, with a triangular form. It corresponds to the mesial part of an osseous pointed tool (Fig. 9b). The spongy area visible on one of the inner surfaces suggests antler as the raw material. Most of the spongy area was removed during the shaping of the point, but the structure still rules out bone as a candidate. Taphonomic alterations, such as slight etching, have enlarged some of the spongy structure (Fig. 10c and d). Longitudinal scraping marks are visible on the distal part (i.e., the tip) and the profile of the point. The cross-section is oval. The distal break is oblique, measuring 3 mm in length and 4 mm in width, and likely occurred in a fresh state and not post-depositionally (Fig. 10e). However, it does not resemble a typical break sustained during use, as described by Pétillon (2006), but it is reminiscent of step hinge fractures with compression damage, which may have occurred during use or maintenance of the artifact (Doyon and Knecht, 2014).

Although most of the proximal end is missing, a linear termination of the fracture plane runs across the cortical thickness along the axis of the maximum width. Rather than dividing the cross-section into two equal halves, the termination is slightly closer to the "outer" cortical surface of the object. While the goal of splitting the base of the SBP is typically to generate wings of similar thickness, comparison of a large sample shows that the split termination is often off-centered relative to the cortical thickness (Doyon, 2017, 2020), which is also the case for the SBP found in AU13. Furthermore, this fracture pattern is not observed in massive-based points (MBPs). Therefore, we tentatively classify this specimen as a split-based point as well.

Morphometric comparisons of the two SBPs with specimens from across Eurasia (Doyon, 2017, 2020; Kitagawa and Conard, 2020; Tejero, 2014) further support their typological attribution. From a metric

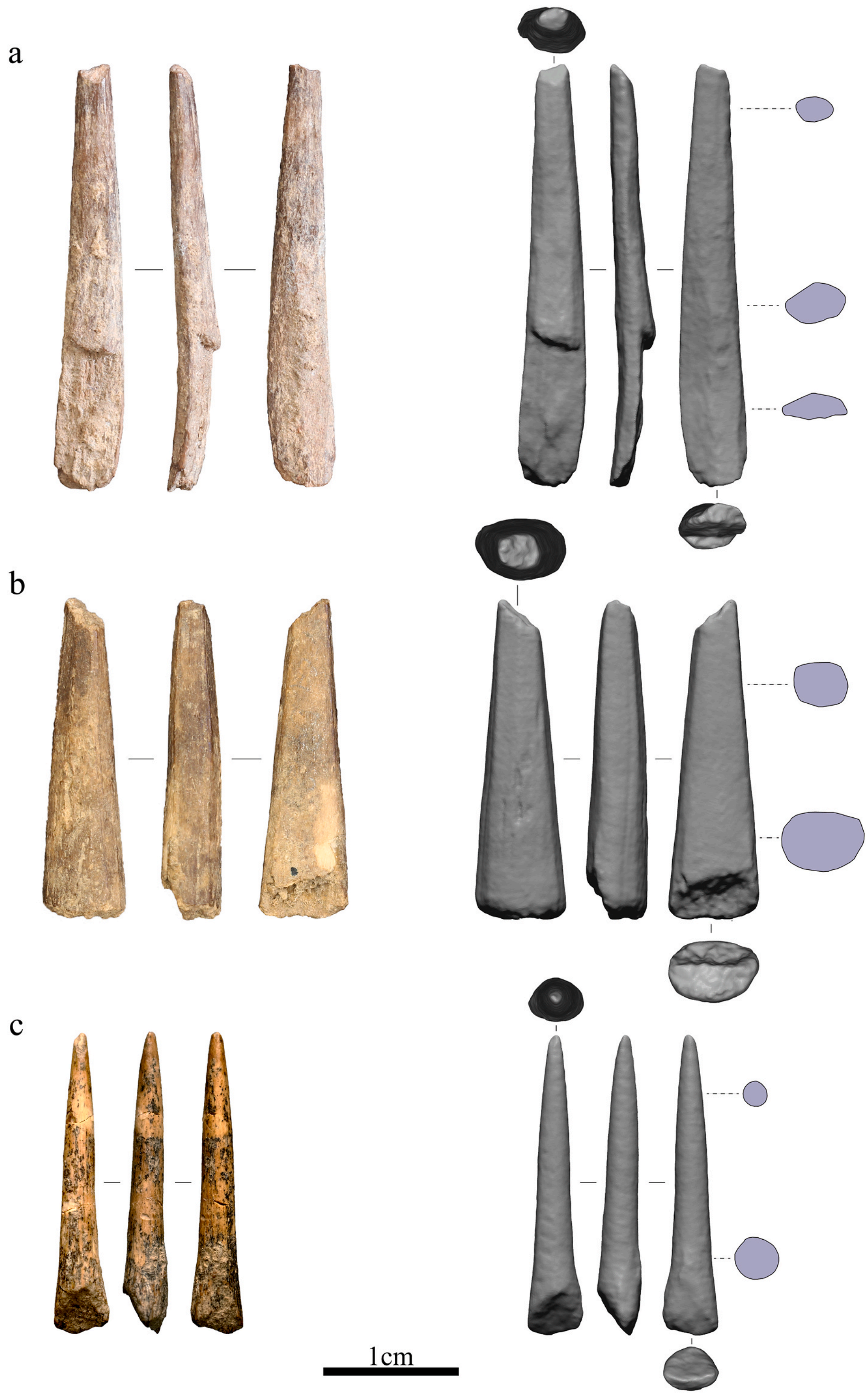

Fig. 9. Photographs and 3D model views of the split-based antler points from AU13 (**a**) and AU12 (**b**), and the bone awl from AU12 (**c**). The 3D views are complemented by cross-sections of the osseous tools, generated in Artifact3-D (Grosman et al., 2022). (Photos by M. Rossini & A. Falcucci).

perspective, the small size of these armatures fits well within the variation documented for SBPs in southern Europe, while they are much smaller than most MBPs reported in the same region. From a morphological perspective, the SBP found in AU13 closely matches some small specimens found at Grotta dei Fanciulli (layer K, accession n° Enf-io–008), Šandalja (layer H, accession n° H Ša-II-81), Vogelherd (layer V, accession n° V 104), and Geißenklösterle (layer IIa, accession n° G 33 IIa 69). The specimen found in AU12 closely matches some specimens from Grotta dei Fanciulli and Grotte de l'Observatoire, although it is roughly half their size in maximum width. The small size of this latter specimen is most likely due to the small dimensions of the original blank, rather than a reduction in size due to resharpening. Newly shaped SBPs typically have a sub-rectangular to oval cross-section, which gradually becomes bi-convex through resharpening (Tejero, 2010).

4.2.2. *The bone awl*

This artifact, found in AU12, measures 21.6 × 3.8 × 2.9 mm and is the second pointed tool discovered in this sub-layer (Fig. 9c). The tool

Fig. 10. Close-up views of the split-based antler points from AU13 (**a**, **b**) and AU12 (**c**, **d**, **e**). (Photos by K. Kitagawa, A. Falcucci, and M. Rossini).

has a round cross-section and represents the distal-mesial part of the original object. The absence of any spongy structure indicates that the raw material is bone, likely from a compact structure. The form, cross-section, and raw material suggest that this pointed tool is part of a bone awl. There is partial black discoloration due to manganese oxide stains. Additionally, some surface loss is visible on the mesial end, possibly due to weathering, and there are no visible manufacturing marks, such as scraping. There is slight micro-splintering at the distal end and a fresh fracture on the mesial end, which is concave in its breakage pattern. Both breaks occurred while the tool's collagen was intact, with the distal fracture likely occurring during use.

4.3. Shells

Out of the 556 malagological remains, a total of 514 shells could be assigned to 57 taxa (Table 7). Except for *Nassarius gibbosulus* and *Tritia* cfr. *lima*, which are currently more restricted to the eastern coastlines of the Mediterranean (modern Greece, Lebanon, Syria, and Egypt), all the identified species are found throughout the Mediterranean Sea. The species identified indicate coastal environments characterized by both rocky cliffs and sandy, detrital seabeds. The infralittoral coastal zone serves as the habitat for the most common species at La Cala (Fig. 11), including *Antalis dentalis/inaequicostata* (NISP = 30), *Homalopoma sanguineum* (NISP = 89), *Tritia mutabilis* (NISP = 24), *Glycymeris nummaria* (NISP = 46), and *Pecten jacobeus* (NISP = 70). Notably, there is evidence of interest in gathering small-sized species, as indicated by the most common morphologies found at the site. This is especially evident in gastropods, where turbinated forms (such as *H. sanguineum*, *Clanculus corallinus*, and *Gibbula ardens*; Fig. 11f) were more prevalent. Additionally, small dimensions are also seen in the *Scaphopoda* class, where the most abundant species, *A. dentalis/inaequicostata*, reaches a height of approximately 15 mm. Among *Bivalvia*, most species exceeded 2 cm in height.

Among the analyzed shells, 58 specimens bear evidence of human perforation, likely for ornamental purposes. Table S17 shows the relative abundances of *H. sanguineum* (48.3 %), *Tritia neritea* (10.3 %), and *G. nummaria* (10.3 %) among the 58 perforated shell beads.

5. Discussion

5.1. Lithic reduction strategies and intra-site diachronic variability

La Cala contains one of the most remarkable Late Pleistocene sequences in Italy. However, until recently, the site received little attention in discussions about the development of the Aurignacian, mainly due to previous dating anomalies and the lack of a technological assessment of the lithic assemblages and osseous tools. The recent redating of the archaeological sequence by Higham et al. (2024), along with this new integrated study, has addressed these gaps, providing significant new insights. Based on the techno-typological features of the lithic assemblages and osseous tools and the new dates, AU13–AU10 can be confidently assigned to the EA.

The most defining feature of the lithic assemblages from AU13–AU10 is the prominent use of carinated technology to produce small-sized bladelets, which rarely exhibit twisted profiles. The frequent use of a unidirectional reduction pattern facilitated the production of bladelets

Table 7
Taxon distribution in the Aurignacian at Grotta della Cala. Numbers in parentheses indicate specimens with signs of anthropic perforation. Values followed by question marks represent holes that are uncertainly attributed due to calcite concretion or post-depositional damage on the shells.

	AU10			AU11			AU12			AU13		
	NISP	MNI	MNV	NISP	MNI	MNV	NISP	MNI	MNV	NISP	MNI	MNV
Gasteropoda												
Gastropoda undet.	2	1		5			5			5		
Patella ulyssiponensis										1	1	
Haliotis tuberculata lamellosa	1	1					1	1		1	1	
Trochidae undet.				1	1		1					
Gibbula ardens										3	3 (1)	
Jujubinus sp.										1	1	
Jujubinus cfr. *striatus striatus*										1	1	
Phorcus articulatus				2	2 (1)		1	1		1	1	
Phorcus turbinatus				2	2							
Clanculus sp.				1	1		1			2	1 (1)	
Clanculus corallinus							2	2 (1)		2	2	
Bolma rugosa							3	2				
Homalopoma sanguineum	10	5 (1)		17	16 (1)		20	18 (8)		42	41 (18)	
Tricolia speciosa										1	1	
Tricolia tenuis										1	1	
Bittium sp.										1	1	
Cerithium sp.	1	1		1	1					1	1 (1)	
Cerithium vulgatum vulgatum	1	1					1	1				
Cerithium/Potamides sp.										1	1	
Potamides conicus										2	2	
Trivia sp.							1			5		
Trivia cfr. *arctica*							1	1				
Trivia cfr. *mediterranea*				1	1							
Trivia mediterranea										15	14 (2)	
Naticidae undet.										1		
Naticarius sp.							1	1				
Naticarius hebraeus										2	2	
Galeodea echinophora										4	1	
Semicassis saburon							1	1		1	1	
Muricidae undet.							1					
Pusia tricolor										1	1	
Nassariidae undet.										1		
Nassarius gibbosulus				1	1 (1)							
Tritia incrassata							1	1 (1)		1	1 (1)	
Tritia cfr. *lima*										1	1	
Tritia cfr. *mutabilis*										1	1	
Tritia mutabilis	1	1		5	4 (1)		4	4		14	11 (4)	
Tritia neritea	3	3 (2)					2	2		15	15 (4)	
Tritia pellucida										2	2 (1)	
Columbella rustica				1	1		1	1				
Mitrella sp.							1	1				
Conus ventricosus							2	1		1	1 (1)	
Bivalvia												
Bivalvia undet.	1			4			6			7		
Striarca lactea				1		1						
Glycymeris sp.	17			7		1	8		2 (1?)	12		2
Glycymeris nummaria	3		1	15		3 (1?)	22		13 (2?)	6		5 (2?)
Mytilus galloprovincialis				1		1						
Pectinidae undet.							1		1			
Pecten jacobeus	6		2	11		2	27		3 (1?)	26		2
Acanthocardia sp.	3			2			10			1		
Acanthocardia cfr. *tuberculata*							1		1	5		1
Acanthocardia tuberculata	11		1	12		4	3		1			
Callista chione				1		1	2		1	5		
Ruditapes decussatus							1		1			
Chamelea gallina	1		1	1		1				1		1
Scaphopoda												
Antalis vulgaris							1			4		
Antalis dentalis/inaequicostata	2	1		7	2		10	5		11	2	
Total NISP	63	14 (3)	5	99	32 (4)	14 (1?)	143	43 (10)	23 (4?)	209	112 (34)	11 (2?)
Undetermined	17			2			11			12		

with sub-parallel to convergent outlines. Alongside bladelets, we identified several small flakes associated with the maintenance of carinated cores' convexities, a procedure well-documented at various EA sites across Europe (e.g., Chiotti, 2000; Le Brun-Ricalens, 2005). At La Cala, carinated cores typically have wide flaking surfaces, although some examples feature the so-called nosed flaking surfaces. As discussed by Le Brun-Ricalens (2005), this morphological variation in flaking surfaces at La Cala likely reflects reduction intensity rather than an intentional effort to produce bladelets with twisted profiles. The systematic production of twisted bladelets is more commonly associated with later stages of the Aurignacian (Bataille and Conard, 2018; Dinnis et al., 2019). Notably, very few of the produced bladelets were modified through marginal retouching, a characteristic that is relatively uncommon in the context of the Italian Aurignacian (Palma di Cesnola, 2001).

Fig. 11. Malacological remains found in AU13–AU10. (**a–c**) *Homalopoma sanguineum*; (**d**) *Clanculus* sp.; (**e**) *Tritia neritea*; (**f**) *Gibbula ardens*; (**g**) *Trivia mediterranea*; (**h–i**) *Tritia incrassata*; (**j–k**) *Phorcus articulatus*; (**l**) *Nassarius gibbosulus*; (**m–n**) *Tritia mutabilis*; (**o**) *Bolma rugosa*; (**p**) *Pecten jacobeus*; (**q–t**) *Glycymeris nummaria*; (**u–v**) *Antalis dentalis/inaequicostata*; (**w–x**) *Antalis vulgaris*. (Photos by L. Tassoni).

Evidence of blade production is more ephemeral, as these blanks were rarely produced on-site. This scarcity is likely due to the lack of large-sized nodules near the site, rather than a reduction sequence from blades to bladelets (see Falcucci et al., 2017). If such a reduction sequence had been present, we would expect to find more platform cores (e.g., semi-circumferential and narrow-sided) with bladelet production evidence at the point of discard. Various lines of evidence suggest that blades were often imported as finished tools. For instance, a few blades exhibit high retouching intensity along both edges (i.e., Aurignacian retouch; de Sonneville-Bordes, 1960). Notably, some of these artifacts are made from non-local chert, that is consistent, on a macroscopic basis, with chert from the Maiolica formation, which can be found approximately 200 km away as the crow flies. This finding supports the idea of marked inter-regional mobility among Aurignacian foragers (Blades, 1999; Bon, 2005), underscoring the need for a renewed inter-regional study on raw material variability to better understand these behaviors in southern Italy.

The selective use of raw materials for lithic production is evident when comparing this pattern to on-site flake production, which employed both freehand and bipolar knapping techniques. In addition to detaching thick flakes as blanks for future carinated cores, flake production likely aimed to produce blanks for domestic activities. Some of these flakes were modified through direct marginal retouching, which did not significantly modify the unstandardized shapes of the selected blanks.

Regarding chrono-cultural variation across the AU sub-layers, we observed very little variability among the studied assemblages. Carinated technology for bladelet production remains consistent, as does the overall organization of the lithic technology. This suggests minimal diachronic variability, likely coupled with a relatively rapid sedimentation rate during the formation of the Aurignacian sequence. This interpretation is further supported by the similarity between the new OSL date from AU12 and the radiocarbon date from AU10, as well as the comparable composition of the faunal assemblage along the whole Aurignacian sequence (Benini et al., 1997). In this context, it is reasonable to hypothesize that stable resource availability and environmental conditions contributed to a relatively consistent behavioral adaptation among the Aurignacian foragers in the region.

Despite relative technological stability, the excavated area from lower AU13–AU12 to the upper AU11–AU10 shows a discernible diachronic decrease in occupation density and human presence. Understanding these shifts requires expanding the excavated area, conducting targeted spatial distribution studies, and further exploring zooarchaeological evidence. Future research on site organization development could confirm these trends, reflecting broader changes in settlement patterns and regional mobility strategies at the beginning of the GI8. Alternatively, the decline in occupation density might suggest demographic fluctuations or modifications in local foraging group mobility patterns.

5.2. Osseous tool diversification in the Aurignacian: insights from Grotta della Cala

Although small in sample size, the osseous tool assemblage from La Cala is notable within the context of southern Italy. The recovered tools, consisting of an awl and two SBPs, are fairly common in the Aurignacian. All items exhibit fractures likely sustained through use or maintenance, suggesting they may represent discarded artifacts at the site.

The identification of two SBPs is particularly noteworthy due to their marked chronological significance; they represent the southernmost evidence of this tool type's diffusion in Europe. The use of antler as a raw material for the SBPs aligns with existing evidence. There are very few cases where bones or other materials were used to create SBPs, especially in Aurignacian contexts (e.g., at Fumane: Broglio and Dalmeri, 2005). Most SBPs recovered in Italy come from the sites of Fumane (Bertola et al., 2013; Broglio and Dalmeri, 2005; Falcucci et al., 2020), Mochi (Tejero and Grimaldi, 2015), and Fossellone (Blanc and Segre, 1953). At Fossellone, SBPs were found alongside MBPs, though the absence of modern archaeological excavation at the site prevents a clear determination of whether these artifacts belong to distinct chronological phases. Another notable SBP comes from the site of Salomone in the Abruzzi region (Mussi, 2002; Radmilli, 1977), though associated archaeological data is limited.

The SBPs discovered at La Cala are among the smallest specimens found in the Aurignacian, especially when compared to examples from Italy (Bertola et al., 2013; Tejero and Grimaldi, 2015) and beyond (Doyon, 2017; Tejero, 2014). Other small SBPs come from Fossellone in the Circeo region (Latium, central Italy), although observations rely solely on drawings by Blanc and Segre (1953). It is worth noting that SBPs exhibit a wide size distribution, and recent studies encompassing hundreds of specimens have revealed significant morphometric variation (Doyon, 2017; Tejero, 2014). For example, complete SBPs studied by Tejero (2014) measure between 50 mm and 110 mm in length, though smaller examples also exist. Smaller SBPs are more frequently found in the Swabian Jura, southwestern Germany, with some specimens measuring approximately 35 mm in length (Kitagawa and Conard, 2020). Another example of a small-sized point (ca. 35 mm in length) comes from Potočka zijalka (Moreau et al., 2015).

This size variation may be linked to several factors, including the species of prey hunted and differences in hafting methods. Larger SBPs were likely hafted differently from smaller ones, suggesting diverse hafting and/or hunting techniques (Odar, 2011; Tartar and White, 2013). Experimental studies, such as those reported by Yeshurun et al. (2024), could provide further insights into this variability, especially with the recovery of new SBPs in varied contexts. Additionally, large variations in size and shape may be significantly influenced by maintenance, recycling, and reuse over time. In some cases, SBPs originally made larger were reduced in size through resharpening after repeated use (Doyon and Katz Knecht, 2014; Tejero, 2014).

It is also worth noting that several scholars classify antler points as SBPs even in the absence of a fully preserved proximal end. For example, Tejero and Grimaldi (2015) list four SBPs at Mochi, although only one has a preserved proximal side. According to a geometric morphometric study by Doyon (2019), the distal (penetrating) portions of SBPs and MBPs show considerable overlap morphologically and metrically, complicating detailed classifications of fragmented tools. This issue is further compounded by the significant above-mentioned morphometric variability of SBPs (Doyon, 2019; Liolios, 2006). Nevertheless, metric data compiled by Doyon (2017) from over 500 osseous points indicate that SBPs are statistically smaller than MBPs in all linear dimensions. Given the stratigraphic proximity and similar dimensions of the fragmented antler point from La Cala to the other SBP, it is very likely that the antler fragment from AU12 also had a split at the base. The same reasoning applies to the antler points from the lower spits of stratigraphic unit F at Mochi, although caution is warranted for fragments from the upper spits of unit F due to its broad temporal span and other archaeological considerations (see below and Douka et al., 2012; Frouin et al., 2022).

5.3. The chrono-stratigraphic distribution of split-based points in the European Aurignacian

Since its initial description at the site of Aurignac by Lartet (1860), the SBP has garnered significant attention in Aurignacian studies. Initially believed to signal the early spread of *Homo sapiens* across Europe (Mellars, 2004), research has since demonstrated that its geographic and chronological distribution does not align with human dispersal events (Davies et al., 2015; Doyon, 2020). Instead, the SBP appears to have emerged at the beginning of the EA, leading several scholars to consider it a type fossil of this Aurignacian phase (Dinnis et al., 2019; Teyssandier and Zilhão, 2018). According to Banks et al. (2013a), SBPs are a vital marker for identifying EA assemblages, as lithics tend to vary more according to site function.

To date, more than 700 SBPs have been documented across Europe, with approximately three-quarters originating from southwestern France (Liolios, 2006). For instance, over 150 SBPs have been recorded at Isturitz and La Quina-Aval (Tejero, 2014). Other regions with high densities of antler points include Cantabria in northern Spain and the Swabian Jura in southwestern Germany. In contrast, few SBPs are documented south of the Alps. Due to this uneven distribution, relying solely on SBPs to identify EA contexts can be challenging if not corroborated by additional evidence. However, antler point production remains a valuable marker for assessing chrono-cultural variability in the Early Upper Paleolithic. For example, in southern Italy, despite the presence of red deer in both the Uluzzian and PA (Boscato and Crezzini, 2012), no SBPs have been documented in sequences predating the EA at La Cala (Arrighi et al., 2020c; Borgia et al., 2017).

Some researchers have questioned the exclusive association of SBPs with EA assemblages based on stratigraphic, archaeological, and chronological data. Doyon (2020), for example, observed that SBPs also appear in PA and later Aurignacian contexts. Direct radiocarbon dating of two SBP wings at Trou de la Mère Clochette (Szmidt et al., 2010) and of an SBP at Divje babe I (Moreau et al., 2015) suggests a wide chronological range, from approximately 41,000 to 31,500 cal BP. However, Teyssandier & Zilhão (2018) have questioned the archaeological data from both sites. At Trou de la Mère Clochette, the PA assemblage was reconstructed from an early 20th-century excavation, and the radiocarbon dates obtained, OxA-19621 (33,750 ± 350) and OxA-19622 (35,460 ± 250), span a broad temporal range, possibly indicating two accumulation events. Using the `R_Combine` function in OxCal v.4.4, we obtained a chronological range for the SBPs at Trou de la Mère Clochette between 40,650 and 39,655 cal BP (at 95 % probability), which is not significantly older than other layers with SBPs and aligns with the PA–EA transition as modeled by Banks et al. (2013a). It is also interesting to note that the SBP at Trou de la Mère Clochette has a circular cross-sectional morphology, which is a less common morphology for this tool type. At Divje babe I, the antler point may be more similar to a MBP according to Teyssandier and Zilhão (2018), though Doyon (2020) argues that its split base is clearly intentional.

Stratigraphic information from several sites with SBPs provide further insights. Tejero and Grimaldi (2015) note that out of over 700 known SBPs, fewer than 10 come from layers assigned to the PA (see also Tafelmaier, 2017), and these are never found in the lowermost PA layers but rather near the top of the sequences. This pattern is evident at sites such as Arbreda, Fumane, and Mochi (Doyon, 2020). Arbreda was redated by Wood et al. (2014), who questioned the previously accepted early dates for the PA and suggested the possible presence of an EA assemblage within the PA level H. Similarly, Tejero & Grimaldi (2015) demonstrated that the SBP from the PA stratigraphic unit G at Mochi is located near the boundary with EA stratigraphic unit F. Their findings, along with the identification of antler working only in unit F, led them to conclude that SBPs were not manufactured in the PA. This is supported by the absence of antler points or worked antler at the nearby PA layers of Riparo Bombrini (Riel-Salvatore and Negrino, 2018b). At Fumane, SBPs are also restricted to the upper part of the Aurignacian sequence (Bertola et al., 2013; Falcucci et al., 2020).

Based on these observations, we hypothesize that SBPs began to be systematically produced in Europe after the onset of the PA, likely facilitated by some degree of population interconnectivity (see also Falcucci et al., 2020). Since recent assessments suggest that the PA–EA transition was gradual rather than abrupt (Falcucci et al., 2024a), it would not be surprising to recover additional SBPs from late PA assemblages. For instance, at Isturitz, a possible SBP wing was found in PA layer C4d1 (Teyssandier, 2023), though this is rare compared to the high number of SBPs in EA layers at the same site (Tejero, 2014).

Our findings from southern Italy support the view of the SBP as primarily an EA tool type that spread among foraging groups after 40,000 cal BP, with no clear association to specific environmental settings. For example, at Castelcivita, no SBPs or evidence of antler working were found in pre-CI EA layers *gic* and *ars*. Therefore, the SBPs at La Cala might reflect internal diachronic variability within the EA (see below). However, from a chrono-stratigraphic perspective, these interpretations could be challenged by the presence of an SBP at the bottom of the Aurignacian sequence at Hohle Fels in the Swabian Jura, dated to between 41,700 and 39,000 cal BP (Kitagawa and Conard, 2020). Still, other sites in the region, such as Geißenklösterle (Hahn, 1988), exhibit a stratigraphic pattern more consistent with those observed in western and southern Europe.

5.4. Exploring cultural diversity and social interactions through non-utilitarian objects

The shell assemblage at La Cala is extensive and diverse, offering valuable insights into the use of non-utilitarian objects during the Aurignacian in southern Italy. Gastropods, basket-shaped, and tubular shells are consistently prevalent across the EA sub-layers, with a noticeable preference for small-sized shells, including certain bivalve forms. A decline in biodiversity, particularly among scaphopods and perforated shells, is observed from AU13 to AU10. Some edible taxa are represented among the remains; however, the high degree of pre-depositional alterations – such as marine abrasion, bioerosion, and predation – indicates that these shells were likely collected post-mortem, rather than for consumption. The overall composition of the assemblage, along with clear evidence of careful selection, supports its interpretation as primarily ornamental.

In the literature, many early Upper Paleolithic sites in Europe and the Levant exhibit a common pattern in the exploitation of small shells, with a distinct preference for turbinated (basket-shaped) and tubular forms (Colonese et al., 2011). Examples include Grotta del Cavallo (Arrighi et al., 2020a), Grotta di Castelcivita (Gambassini, 1997), Klissoura (Stiner, 2010), Franchthi (Perlès, 2018), Grotta di Fumane (Peresani et al., 2019a), Mochi (Kuhn and Stiner, 1998; Stiner, 1999), Riparo Bombrini (Holt et al., 2019), Üçağızlı (Kuhn et al., 2009), and Ksar'Akil (Kuhn et al., 2001). In Italy, Aurignacian sites exhibit a diversity of shell ornaments, found at both coastal sites like the Balzi Rossi complex and inland sites like Fumane (Arrighi et al., 2020c). Shells as ornaments appear to be consistent markers of the Aurignacian across Italy, showing little chrono-cultural variability within this technocomplex.

A noteworthy difference between southern and northern Italian sites is the absence of other raw materials for personal ornaments in the south, such as stone (e.g., steatite) and hard animal tissue (e.g., bone, tooth, or ivory), a pattern observed both in the PA and especially in the EA. Northern sites like Fumane (Broglio and Dalmeri, 2005) and Mochi (Tejero and Grimaldi, 2015), as well as central Italian sites like Fossellone (Blanc and Segre, 1953), feature grooved or pierced teeth and stone alongside shells. For example, EA layer 21 at Fossellone includes pierced deer canines, a fox canine, and steatite pendants. Basket-shaped beads, common in southwestern France (Teyssandier, 2023), are only attested in EA unit F at Mochi, where one ivory and three soft stone beads were identified. This reliance on raw materials from southeastern France (Grimaldi et al., 2014) suggests stronger cultural interactions with western regions than with the southeast.

The decreased reliance on materials other than shells in southern Italy may provide insights into the mechanisms behind the development of the Aurignacian. This variability cannot be attributed to a lack of resources, as red deer was abundant in AU13–AU10. Interestingly, the use of shells appears to increase from the PA to the EA in southern Italy. For instance, at Castelcivita, only a few shells were recovered in PA layer *rsa'* ($n = 12$), primarily *P. jacobeus* fragments. In contrast, EA layer *gic* yielded 117 shells, predominantly *H. sanguineum* (42.8 %), followed by *T. mutabilis* (14.2 %) and *Clanculus corallinus* (10.7 %) (Tassoni, 2019).

At a broader European scale, although some scholars suggest that EA personal ornaments are often made from raw materials other than shells (Teyssandier, 2023), shells remain well represented (Taborin, 1993a), even in the Paleolithic of southwestern Germany (Schürch et al., 2021). Additionally, a strong association between SBPs and shells has been noted (Doyon, 2022). Certain SBP morphologies also appear to correlate with specific shell species, highlighting patterns that merit further investigation. Vanhaeren and d'Errico (2006) proposed that personal ornaments act as proxies for ethno-linguistic diversity and carry deep social and symbolic meanings; a view partially echoed by Peresani et al. (2019a) in their discussion of the frequent use of *H. sanguineum* and other reddish-yellow shells in Italian Aurignacian contexts, and by Arrighi et al. (2020a) with regard to task shells in the Uluzzian. These authors interpret this preference as an established communication system shared over a broad area, possibly reflecting ethnic identities.

5.5. The chrono-cultural trajectories of the Aurignacian across Italy

To analyze the EA archaeological evidence across Italy, we compiled a set of radiocarbon dates from EA layers based on available literature (Fig. 12a and SM Note 3). For Mochi, we included dates from stratigraphic unit G, spits 51–50, as they may correspond to an as-yet-undescribed EA layer. However, one date from spit 51 was excluded, as it is considered a minimum date due to possible contamination from the small shell size and insufficient cleaning (Douka et al., 2012). All shell dates from Mochi should be treated as minimum ages, given potential diagenetic alterations and stratigraphic mixing. Unreliable radiocarbon dates were flagged in a recent redating effort that combined C14 and OSL determinations for the entire Mochi sequence (Frouin et al., 2022). Beside the date from spit 51, we also excluded dates from the upper portion of stratigraphic unit F (spits 34–40). Stratigraphic unit F at Mochi, extending into Heinrich Stadial 3, spans approximately 1 m and has been modeled by both Douka et al. (2012) and more recently by Frouin et al. (2022). Interestingly, Douka et al. (2012) hypothesized that an Early Gravettian occupation might be recorded in stratigraphic unit F's upper portion, aligning with the chronological data from other Early Gravettian assemblages known in Italy and beyond (Douka et al., 2020; Falcucci and Peresani, 2019).

The KDE model of EA sites in Italy reveals a broad, bimodal distribution of dates (Fig. 12b). The highest density of dates falls within the earliest EA stages, with the oldest from the pre-CI EA layers at

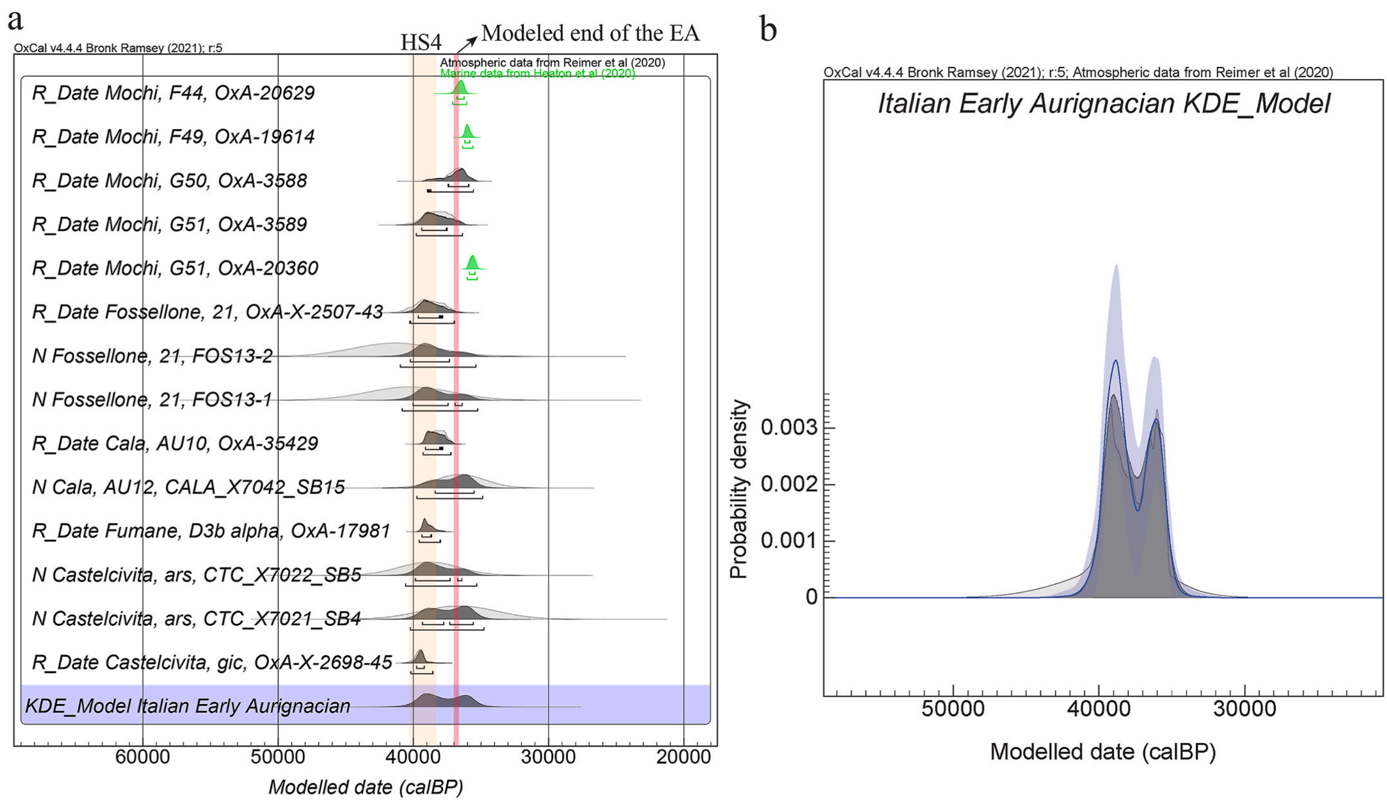

Fig. 12. **a**. Calibrated ages for radiocarbon and OSL dates from Early Aurignacian sites in Italy. The orange bar marks the timing of Heinrich Stadial 4 (HS4), while the red bar indicates the modeled end of the Early Aurignacian by Banks et al. (2013b). **b.** Kernel Density Estimate (KDE) model based on the dates shown in **a**. Both figures were exported from OxCal and modified in Inkscape (https://inkscape.org/) by A. Falcucci. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

Castelcivita, while the youngest dates belong to Mochi. Interestingly, all shell dates appear younger than charcoal dates, as expected, while OSL dates show a much wider range, especially the two from layer 21 at Fossellone. The KDE model generally aligns with Banks et al. (2013b) proposed EA onset at 40,000–39,200 cal BP. However, the younger dates from Mochi's stratigraphic unit F (spits 49–44) do not fit within Banks et al.'s modeled end range for the EA and beginning of the Evolved Aurignacian (37,000–36,500 cal BP). Charcoal dates from Mochi's stratigraphic unit G, spits 51–50, on the other hand, align closely with other EA assemblages. Further technological assessments and stratigraphic integrity studies are necessary to better understand Mochi's place in the development of the Italian Aurignacian. Dating anomalies have also been noted at the nearby site of Bombrini, where PA layers persist until about 36,000 cal BP (Benazzi et al., 2015), marking the only known PA assemblage with such an extended temporal span in Europe. Frouin et al. (2022) hypothesize possible contamination of the dated bones at Bombrini due to low amounts of extracted collagen and high C:N ratios.

With the addition of the new studies at Castelcivita (Falcucci et al., 2024a) and La Cala, the number of sites assigned to the EA has expanded, enhancing our understanding of this crucial phase. Previously, limited evidence led some researchers to consider the EA as relatively scarce in Italy (Degano et al., 2019; Palma di Cesnola, 2001). Notably, at sites where both PA and EA are present, EA layers consistently overlie PA layers (Falcucci et al., 2024a, 2024b; 2025a; Tejero and Grimaldi, 2015). Castelcivita's *gic* and *ars* layers contain Italy's earliest EA assemblages, where Falcucci et al. (2024a) describe a gradual shift from PA to EA technologies, rather than a sharp cultural break. The primary distinction between PA and EA at Castelcivita lies in the increased production of miniaturized bladelets from carinated cores, a technological shift that Falcucci et al. (2024a) argue provided general advantages for foragers, independent of specific environmental factors.

The EA layers at Castelcivita underscore cultural transmission and population connectivity as key factors in the PA–EA shift, rather than population replacement. A unique feature at this site is the frequent modification of miniaturized bladelets by direct marginal retouching, a tool type prevalent in both layers *gic* (ca. 65 %) and *ars* (ca. 55 %). These bladelets have not been observed outside the region, indicating a distinct regional and chronological signature within the EA. In the region, retouched bladelets have been found at Serino (Accorsi et al., 1979) and La Cala (see Fig. 6), albeit in low numbers. While the scarcity of retouched bladelets at La Cala may be partly due to site function, we argue it is unlikely to fully explain their absence across the entire Aurignacian sequence. Instead, we interpret this decrease in bladelet modification as part of a broader trend across Italy and other parts of Europe during the Aurignacian. At Fumane, for example, retouched bladelets decline in the EA layer D3b alpha (Falcucci et al., 2024b), a pattern observed throughout the Aurignacian sequence (Falcucci et al., 2020). Laplace (1977) also observed a similar trend at Mochi, where the upper part of stratigraphic unit G shows a marked decrease in retouched bladelets and an increase in carinated endscrapers. This trend is similarly documented at Isturitz in the Basque Country (Normand, 2006).

A site sub-contemporaneous to La Cala, Fossellone in central Italy, also features carinated bladelet production in the EA layer 21. However, due to outdated excavation standards, many bladelets were not collected. Although the radiocarbon date for this layer has a large standard deviation, Degano et al. (2019) suggest it serves as a minimum age that aligns well with La Cala's dating. Fossellone's use of very small pebbles led to a unique lithic technology within the Aurignacian, as also noted at nearby Grotta Barbara (D'Angelo and Mussi, 2005). The bipolar technique on anvil was necessary to produce bladelets from small pebbles, resulting in bladelets shorter than 20 mm and 3–5 mm in width

(Degano et al., 2019). Of 860 endscrapers at Fossellone, Blanc & Segre (1953) report 582 (ca. 68 %) carinated types, including 112 thick-nosed endscrapers. Degano et al. (2019) attribute the thick-nosed forms to raw material constraints rather than a need for twisted bladelets. Only one retouched bladelet was recorded at Fossellone, though the aforementioned excavation limitations should be considered.

Riparo Mochi on the Ligurian coast may illustrate another progressive shift to the EA. However, Mochi's chronological and archaeological data present challenges. Laplace (1977) noted a clear trend towards decreased retouched bladelets in the upper part of stratigraphic unit G. These bladelets were typically retouched directly, as opposed to the inverse retouching common in lower PA layers, aligning with data from Fumane and Castelcivita (Falcucci et al., 2020, 2024a, 2024b). The decline in retouched bladelets from stratigraphic units G to F (41 %–6 %) corresponds with an increase in endscrapers (7 %–34 %), many of which were carinated and likely used for bladelet production. This interpretation is supported by Laplace's observation of fewer cores in these upper Aurignacian spits, indicating reliance on carinated endscrapers for lamellar production (Laplace, 1977).

In light of these observations, alongside the available radiocarbon dates and the presence of an SBP at the top of stratigraphic unit G, we propose that the EA at Mochi likely began in the upper spits of stratigraphic unit G. This scenario is plausible, considering that, in Italian research tradition, multiple assemblages have been often grouped under the term "Aurignacian with marginally retouched bladelets" (i.e., the PA) solely due to the presence of a few retouched bladelets. This term has historically been applied to a broad range of assemblages spanning a significant chronological period, as discussed in Teyssandier and Zilhão (2018).

Grotta Paglicci in Apulia offers another example within this framework. Here, the Aurignacian sequence is capped by the Codola tephra, dating to ca. 33,000 cal BP (Giaccio et al., 2008). The underlying layer 24 A1–0, dated to 34,454–33,075 cal BP, is one of Italy's few later Aurignacian examples. Layer 24's lower part (BII–I) may relate to the EA, though limited excavation yielded a small assemblage (Palma di Cesnola, 2004). Carinated cores and miniaturized bladelets in layer 24 BII–I resemble the EA as described at La Cala. Available dates, such as 39,956–37,628 cal BP, support this attribution despite the large standard deviation (34,000 ± 900). We are currently re-analyzing Paglicci's layer 24 to provide an updated archaeological and techno-typological perspective.

6. Conclusions

This study presents a comprehensive reassessment of Grotta della Cala, one of Europe's southernmost Aurignacian sites. While initially excavated in the 1970s, recent excavations led by one of us (AM) have provided critical new evidence that resolves previous dating inconsistencies (Higham et al., 2024) and offers a more accurate characterization of the Aurignacian sequence at the site. By analyzing bone, lithic, and shell assemblages from AU13–AU10, we have confidently assigned this sedimentary complex to the Early Aurignacian, a conclusion further supported by new radiocarbon and OSL dating. This interpretation enhances the understanding of Grotta della Cala and the nearby Grotta di Castelcivita as pivotal in studying the behavioral development of Paleolithic foraging groups, particularly in the transition from the Protoaurignacian to the Early Aurignacian. These findings underscore the importance of southern Italy in reconstructing the cultural dynamics of the early Upper Paleolithic.

At Grotta della Cala, Early Aurignacian assemblages show significant continuity across the studied sub-layers, suggesting a stable and adaptive technological system capable of responding to environmental changes. When combined with data from Grotta di Castelcivita, our study reveals a gradual shift from the Protoaurignacian technological system, marked by an increased reliance on carinated technology and the expanded use of animal hard tissues. Notably, the recovery of two split-based points—a hallmark of the Early Aurignacian—strengthens this interpretation. Overall, the transition from the Protoaurignacian to the Early Aurignacian emerges as a gradual process, characterized by regional variations and chronological flexibility. This pattern is consistent with broader trends observed across western and southern European sites, evidenced by the general lack of interstratified Protoaurignacian and Early Aurignacian assemblages.

While future paleogenetic studies may offer new insights, we argue that the transition from Protoaurignacian to Early Aurignacian in southern Italy likely did not involve population replacement, despite environmental challenges such as the Campanian Ignimbrite super-eruption. The continuity in technology and cultural practices, particularly the persistent use of marine shells as personal ornaments, suggests that these changes occurred within a culturally stable framework. Our findings raise important questions about the cultural mechanisms that facilitated the spread of technological innovations among geographically dispersed foraging groups. Comparative studies across other sites will be essential to assess cultural connectivity and understand the role of environmental and geographic factors in shaping regional networks and social interactions. Resolving chronological uncertainties at key sites will further refine our understanding of this dynamic period.

Author contributions

A.F. designed the study. A.F. analyzed the lithic assemblages and conducted data exploration and statistical investigations in R. K.K., L.D., C.D., D.D., and A.F. analyzed the osseous tools. L.T. analyzed the shell assemblage. I.M. conducted the sedimentological and allostratigraphic study of the cave. A.F. wrote the original manuscript with contributions from K.K., L.T., L.D., I.M., J.C., F.B., and A.M. A.F., K.K., V.S., I.M., M.R., L.T., and A.M. produced the figures for the paper. A.M. is the director of the scientific research project and the fieldwork at Grotta dell Cala. All authors read, revised, and approved the final version of the manuscript.

Funding

Research and fieldwork at Grotta della Cala have been funded by the University of Siena and the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 724046; http://www.ercsuccess.eu/; PI: S. Benazzi), as well as by the PRIN TRACE project (PIs: S. Benazzi and A. Moroni) and the National Geographic Society/Exploration Grant Program (grant NGS-61617R-19; PI: I. Martini). Analyses of lithic and osseous tools were supported by the German Research Foundation (DFG) under grant agreement no. 431809858 (project title: *Investigating Early Upper Paleolithic Technological Variability and Cultural Dynamics South of the Alps*; PI: A. Falcucci; https://gepris.dfg.de/gepris/projekt/431809858?language=en). MicroCT measurements were acquired with support from the ELETTRA proposal 20225390 (PI: C. Dominici) and the CERIC proposal 20227232 (PI: C. Dominici). We acknowledge Elettra Sincrotrone Trieste and the CERIC-ERIC Consortium for providing access to experimental facilities and financial support. L. Doyon acknowledges the scientific framework and financial support provided by the European Research Council Starting Grant for the project *Pleistocene Expedient Osseous Technology* (ExOsTech, No. 101161065), the IdEx "Talent" programme, and the *Grands Programmes de Recherche* (GPR) "Human Past" at the University of Bordeaux. K. Kitagawa would like to thank the GfU committee for travel funding support. Open Access funding was enabled and organized by Projekt DEAL at the University of Tübingen.

Declaration of competing interest

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.

Acknowledgments

We extend our heartfelt remembrance to Paolo Gambassini, whose dedication and professionalism made this study possible. We thank Annamaria Ronchitelli for her valuable advice during the writing of this article. Our gratitude goes to the *Soprintendenza Archeologia Belle Arti e Paesaggio* for the provinces of Salerno and Avellino for their permissions and ongoing support of the decades-long research conducted by the University of Siena at Grotta della Cala. We are also thankful to the researchers and students who have actively contributed to the excavations at Grotta della Cala over the years. Finally, we acknowledge the Municipality of Camerota, particularly Mayor Dr. Mario Salvatore Scarpitta and Councillor for Culture Dr. Teresa Esposito, for their logistical support. Ongoing research at Grotta della Cala is conducted under the permission of MiC (MIC|MIC_DG-ABAP_SERV II|September 30, 2021|0032649-P| [34.61.07/1.14.1/2019]).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2025.109471.

Data availability

The datasets generated and analyzed in the current study are available in the associated research compendium on Zenodo: https://doi.org/10.5281/zenodo.15430431. The repository includes the R scripts to reproduce all results, figures, and tables of the study. Furthermore, the analyzed 3D models are published in Zenodo: https://doi.org/10.5281/zenodo.14165189.

References

Accorsi, C.A., Aiello, E., Bartolini, C., Castelletti, L., Rodolfi, G., Ronchitelli, A., 1979. Il giacimento paleolitico di Serino, Avellino: stratigrafia e paletnologia. Atti della Societa Toscana di Scienze Naturali 86, 435–487.

Anderson, L., Bon, F., Bordes, J.-G., Pasquini, A., Slimak, L., Teyssandier, N., 2015. Relier des espaces, construire de nouveaux réseaux : aux origines du Protoaurignacien et des débuts du Paléolithique supérieur en Europe occidentale. In: Naudinot, N., Meignen, L., Binder, G., et al. (Eds.), Les Systèmes De Mobilité De La Préhistoire Au Moyen Âge Xxxve Rencontres Internationales D'Archéologie Et D'Histoire D'Antibes. Éditions APDCA, Antibes, pp. 57–73.

Andrefsky, W., 1998. Lithics: Macroscopic Approaches to Analysis. Cambridge University, Cambridge.

Arrighi, S., Bortolini, E., Tassoni, L., Benocci, A., Manganelli, G., Spagnolo, V., Foresi, L. M., Bambini, A.M., Lugli, F., Badino, F., Aureli, D., Boschin, F., Figus, C., Marciani, G., Oxilia, G., Silvestrini, S., Cipriani, A., Romandini, M., Peresani, M., Ronchitelli, A., Moroni, A., Benazzi, S., 2020a. Backdating systematic shell ornament making in Europe to 45,000 years ago. Archaeol. Anthropol. Sci. 12, 59. https://doi.org/10.1007/s12520-019-00985-3.

Arrighi, S., Marciani, G., Rossini, M., Pereira Santos, M.C., Fiorini, A., Martini, I., Aureli, D., Badino, F., Bortolini, E., Figus, C., Lugli, F., Oxilia, G., Romandini, M., Silvestrini, S., Ronchitelli, A., Moroni, A., Benazzi, S., 2020b. Between the hammerstone and the anvil: bipolar knapping and other percussive activities in the late Mousterian and the Uluzzian of Grotta di Castelcivita (Italy). Archaeol. Anthropol. Sci. 12, 271. https://doi.org/10.1007/s12520-020-01216-w.

Arrighi, S., Moroni, A., Tassoni, L., Boschin, F., Badino, F., Bortolini, E., Boscato, P., Crezzini, J., Figus, C., Forte, M., Lugli, F., Marciani, G., Oxilia, G., Negrino, F., Riel-Salvatore, J., Romandini, M., Peresani, M., Spinapolice, E.E., Ronchitelli, A., Benazzi, S., 2020c. Bone tools, ornaments and other unusual objects during the middle to upper Palaeolithic transition in Italy. Quat. Int. 551, 169–187. https://doi.org/10.1016/j.quaint.2019.11.016.

Azzi, C.M., Gulisano, F., 1979. Florence radiocarbon dates IV. Radiocarbon 21, 353–357.

Azzi, C.M., Bigliocca, L., Piovan, E., 1973. Florence radiocarbon dates I. Radiocarbon 15, 479–487.

Azzi, C.M., Bigliocca, L., Gulisano, F., 1977. Florence radiocarbon dates III. Radiocarbon 19, 165–169.

Banks, W.E., d'Errico, F., Zilhão, J., 2013a. Human-climate interaction during the early upper Palaeolithic: testing the hypothesis of an adaptive shift between the proto-Aurignacian and the Early Aurignacian. J. Hum. Evol. 64. https://doi.org/10.1016/j.jhevol.2013.01.001, 232-232.

Banks, W.E., d'Errico, F., Zilhão, J., 2013b. Revisiting the chronology of the Proto-Aurignacian and the Early Aurignacian in Europe: a reply to Higham et al.'s comments on Banks et al. (2013). J. Hum. Evol. 65, 810–817. https://doi.org/10.1016/j.jhevol.2013.08.004.

Bar-Yosef, O., Zilhão, J., 2006. Towards a Definition of the Aurignacian. Instituto Português de Arqueologia, Lisbon.

Bataille, G., Conard, N.J., 2018. Blade and bladelet production at Hohle Fels Cave, AH IV in the Swabian Jura and its importance for characterizing the technological variability of the Aurignacian in Central Europe. PLoS One 13, e0194097. https://doi.org/10.1371/journal.pone.0194097.

Benazzi, S., Slon, V., Talamo, S., Negrino, F., Peresani, M., Bailey, S.E., Sawyer, S., Panetta, D., Vicino, G., Starnini, E., Mannino, M.A., Salvadori, P.A., Meyer, M., Paabo, S., Hublin, J.J., 2015. The makers of the Protoaurignacian and implications for Neandertal extinction. Science 348, 793–796. https://doi.org/10.1126/science.aaa2773.

Benini, A., 1995. Grotta della Cala (Prov. di Salerno). Paletnologia Ed Ambiente Dei Livelli Aurignaziani. Università Di Siena.

Benini, A., Boscato, P., Gambassini, P., 1997. Grotta Della Cala (Salerno): Industrie Litiche E Faune Uluzziane Ed Aurignaziane, vol. 48. Rivista di Scienze Preistoriche, pp. 37–95.

Bertola, S., Broglio, A., Cristiani, E., De Stefani, M., Gurioli, F., Negrino, F., Romandini, M., Vanhaeren, M., 2013. La diffusione del primo Aurignaziano a sud dell'arco alpino. Preistoria Alp. 47, 17–30.

Bertola, S., Visentin, D., Fontana, F., 2018. Lithic raw material circulation and settlement dynamics in the upper Palaeolithic of the venetian Prealps (NE Italy). A key-role for palaeoclimatic and landscape changes across the LGM? In: Borgia, V., Cristiani, E. (Eds.), Palaeolithic Italy. Advanced Studies on Early Human Adaptations in the Apennine Peninsula. Sidestone Press, Leiden, pp. 219–246.

Blades, B., 1999. Aurignacian settlement patterns in the Vezere Valley. Curr. Anthropol. 40, 712–719. https://doi.org/10.1086/300090.

Blanc, A.C., Segre, A.G., 1953. Excursion au Mont Circé. INQUA, IV° International congress. Roma-Pisa.

Bon, F., 2005. Little big tool. Enquete autour du succés de la lamelle. In: Le Brun-Ricalens, F. (Ed.), Productions Lamellaires Attribuées À L'Aurignacien. MNHA, Luxembourg, pp. 479–484.

Bon, F., Bodu, P., 2002. Analyse technologique du débitage aurignacien. In: Schmider, B. (Ed.), L'Aurignacien De La Grotte Du Renne. Les Fouilles D'André Leroi-Gourhan À Arcy-sur-Cure (Yonne). CNRS, Paris, pp. 115–133.

Bon, F., Teyssandier, N., Bordes, J.-G., 2010. La signification culturelle des équipements lithiques. In: Otte, M. (Ed.), Les Aurignaciens. Errance, Paris, pp. 46–65.

Borgia, V., Boschin, F., Ronchitelli, A., 2016. Bone and antler working at Grotta Paglicci (Rignano Garganico, Foggia, southern Italy). Quat. Int. 403, 23–39. https://doi.org/10.1016/j.quaint.2015.11.116.

Borgia, V., Crezzini, J., Ronchitelli, A., 2017. Grotta del Cavallo (LE): strumento in osso inedito dell'Uluzziano antico. Studi di Preistoria e Protostoria 4, 663–667.

Boscato, P., Crezzini, J., 2012. Middle–Upper Palaeolithic transition in Southern Italy: uluzzian macromammals from Grotta del Cavallo (Apulia). Quat. Int. 252, 90–98. https://doi.org/10.1016/j.quaint.2011.03.028.

Boscato, P., Ronchitelli, A., Wierer, U., 1997. Il Gravettiano Antico Della Grotta Della Cala a Marina Di Camerota, Paletnologia E Ambiente, 48. Rivista di Scienze Preistoriche, pp. 97–183.

Boschin, F., Boscato, P., Berto, C., Crezzini, J., Ronchitelli, A., 2018. The palaeoecological meaning of macromammal remains from archaeological sites exemplified by the case study of Grotta Paglicci (Upper Palaeolithic, southern Italy). Quat. Res. 90, 470–482. https://doi.org/10.1017/qua.2018.59.

Broglio, A., Dalmeri, G., 2005. Pitture paleolitiche nelle Prealpi Venete: Grotta di Fumane e Riparo Dalmeri. In: Memorie Del Museo Civico Di Storia Naturale Di Verona, 2a Serie, vol. 9. Sezione Scienze dell'Uomo, Verona.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51, 337–360. https://doi.org/10.1017/S0033822200033865.

Bronk Ramsey, C., 2017. Methods for summarizing radiocarbon datasets. Radiocarbon 59, 1809–1833. https://doi.org/10.1017/RDC.2017.108.

Bronk Ramsey, C., Lee, S., 2013. Recent and Planned Developments of the Program OxCal. Radiocarbon 55 (2–3), 2013.

Cascalheira, J., 2019. Territoriality and the organization of technology during the Last Glacial Maximum in southwestern Europe. PLoS One 14, e0225828. https://doi.org/10.1371/journal.pone.0225828.

Chiotti, L., 2000. Dufour bladelets and Aurignacian endscrapers (carinate and nose-ended) from Level 8 of abri Pataud, Les Eyzies-de-Tayac, Dordogne. Anthropologie (Brno) 104, 239–263.

Collina, C., Marciani, G., Martini, I., Donadio, C., Repola, L., Bortolini, E., Arrighi, S., Badino, F., Figus, C., Lugli, F., Oxilia, G., Romandini, M., Silvestrini, S., Piperno, M., Benazzi, S., 2020. Refining the Uluzzian through a new lithic assemblage from Roccia San Sebastiano (Mondragone, southern Italy). Quat. Int. https://doi.org/10.1016/j.quaint.2020.03.056.

Colonese, A.C., Mannino, M.A., Bar-Yosef Mayer, D.E., Fa, D.A., Finlayson, J.C., Lubell, D., Stiner, M.C., 2011. Marine mollusc exploitation in Mediterranean prehistory: an overview. Quat. Int. 239, 86–103. https://doi.org/10.1016/j.quaint.2010.09.001.

Conard, N.J., 2009. A female figurine from the basal Aurignacian of Hohle Fels Cave in southwestern Germany. Nature 459, 248–252. https://doi.org/10.1038/nature07995.

Conard, N.J., Adler, D.S., 1997. Lithic reduction and hominid behavior in the middle Paleolithic of the rhineland. J. Anthropol. Res. 53, 147–175. https://doi.org/10.1086/jar.53.2.3631275.

D'Angelo, E., Mussi, M., 2005. Galets et lamelles de l'Aurignacien du Latium (Italie Centrale): le cas de Grotta Barbara. In: Le Brun-Ricalens, F. (Ed.), Productions Lamellaires Attribuées À L'Aurignacien. MNHA, Luxembourg, pp. 313–322.

d'Errico, F., Borgia, V., Ronchitelli, A., 2012. Uluzzian bone technology and its implications for the origin of behavioural modernity. Quat. Int. 259, 59–71. https://doi.org/10.1016/j.quaint.2011.03.039.

Davies, W., White, D., Lewis, M., Stringer, C., 2015. Evaluating the transitional mosaic: frameworks of change from Neanderthals to Homo sapiens in eastern Europe. Quat. Sci. Rev. 118, 211–242. https://doi.org/10.1016/j.quascirev.2014.12.003.

de Sonneville-Bordes, D., 1960. Le Paléolithique Supérieur En Périgord. Delmas, Bordeaux.

Degano, I., Soriano, S., Villa, P., Pollarolo, L., Lucejko, J.J., Jacobs, Z., Douka, K., Vitagliano, S., Tozzi, C., 2019. Hafting of Middle Paleolithic tools in Latium (central Italy): new data from Fossellone and Sant'Agostino caves. PLoS One 14, e0213473. https://doi.org/10.1371/journal.pone.0213473.

Delpiano, D., Marciani, G., Conforti, J., Lombardo, S., Rossini, M., Santos, M.C.P., Benazzi, S., Peresani, M., Moroni, A., 2024. Not just a technique! an experimental approach to refine the definition of the bipolar anvil reduction in the Uluzzian. Archaeol. Anthropol. Sci. 16, 202. https://doi.org/10.1007/s12520-024-02097-z.

Demars, P.-Y., Laurent, P., 1992. Types d'outils lithiques du Paléolithique supérieur en Europe. In: Cahiers Du Quaternaire, vol. 14. CNRS, Paris.

Di, Pasquale G., Saracino, A., Bosso, L., Russo, D., Moroni, A., Bonanomi, G., Allevato, E., 2020. Coastal pine-oak glacial refugia in the Mediterranean Basin: a biogeographic approach based on charcoal analysis and spatial modelling. Forests 11, 673.

Dinnis, R., Bessudnov, A., Chiotti, L., Flas, D., Michel, A., 2019. Thoughts on the structure of the European Aurignacian, with particular focus on hohle fels IV. Proc. Prehist. Soc. 85, 29–60. https://doi.org/10.1017/ppr.2019.11.

Doneddu, M., Trainito, E., 2005. Conchiglie del Mediterraneo. Il Castello, Trezzano Sul Naviglio.

Douka, K., Grimaldi, S., Boschian, G., del Lucchese, A., Higham, T., 2012. A new chronostratigraphic framework for the Upper Palaeolithic of Riparo Mochi (Italy). J. Hum. Evol. 62, 286–299. https://doi.org/10.1016/j.jhevol.2011.11.009.

Douka, K., Chiotti, L., Nespoulet, R., Higham, T., 2020. A refined chronology for the Gravettian sequence of Abri Pataud. J. Hum. Evol. 141, 102730. https://doi.org/10.1016/j.jhevol.2019.102730.

Doyon, L., 2017. La Variabilité Technologique Et Morphométrique Des Pointes De Projectile Aurignaciennes En Matière Osseuse. Université de Bordeaux and Université de Montréal. Ph.D. Dissertation.

Doyon, L., 2019. On the shape of things: a geometric morphometrics approach to investigate Aurignacian group membership. J. Archaeol. Sci. 101, 99–114. https://doi.org/10.1016/j.jas.2018.11.009.

Doyon, L., 2020. The cultural trajectories of Aurignacian osseous projectile points in Southern Europe: insights from geometric morphometrics. Quat. Int. 551, 63–84. https://doi.org/10.1016/j.quaint.2018.12.010.

Doyon, L., 2022. Le paysage socio-symbolique aurignacien : regards croisés entre les parures, les symboles et la morphologie des armatures en matière osseuse. Bull. Mus. Anthropol. préhist. Monaco 61, 85–94.

Doyon, L., Katz Knecht, H., 2014. The effects of use and resharpening on morphometric variability of aurignacian antler projectile points. Mitteilungen der Gesellschaft für Urgeschichte 23, 83–101.

Doyon, L., Knecht, H., 2014. The effects of use and resharpening on morphometric variability of aurignacian antler projectile points. Mitteilungen der Gesellschaft für Urgeschichte 23, 83–101.

Dutkiewicz, E., Wolf, S., Floss, H., Conard, N.J., 2018. Les objets en ivoire du Jura souabe. L'Anthropologie 122, 447–468. https://doi.org/10.1016/j.anthro.2018.05.003.

D'Angelo, G., Gargiullo, S., 1987. Guida Alle Conchiglie Mediterranee: Conoscerle Cercarle Collezionarle. Fabbri, Milano.

Falcucci, A., Moroni, A., 2025. The open aurignacian Project. Grotta della Cala in southern Italy (v.1.0.1). Zenodo 3. https://doi.org/10.5281/zenodo.14165189.

Falcucci, A., Moroni, A., Negrino, F., Peresani, M., Riel-Salvatore, J., 2025b. The Open Aurignacian Project: 3D scanning and the digital preservation of the Italian Paleolithic record. Scientific Data 12, 1037. https://doi.org/10.1038/s41597-025-05330-z.

Falcucci, A., Peresani, M., 2018. Protoaurignacian Core reduction procedures: blade and bladelet technologies at fumane Cave. Lithic Technol. 43, 125–140. https://doi.org/10.1080/01977261.2018.1439681.

Falcucci, A., Peresani, M., 2019. A pre-heinrich Event 3 assemblage at Fumane Cave and its contribution for understanding the beginning of the Gravettian in Italy. Quartar 66, 135–154. https://doi.org/10.7485/QU66_6.

Falcucci, A., Peresani, M., 2022. The contribution of integrated 3D model analysis to Protoaurignacian stone tool design. PLoS One 17, e0268539. https://doi.org/10.1371/journal.pone.0268539.

Falcucci, A., Conard, N.J., Peresani, M., 2017. A critical assessment of the Protoaurignacian lithic technology at Fumane Cave and its implications for the definition of the earliest Aurignacian. PLoS One 12, e0189241. https://doi.org/10.1371/journal.pone.0189241.

Falcucci, A., Peresani, M., Roussel, M., Normand, C., Soressi, M., 2018. What's the point? Retouched bladelet variability in the Protoaurignacian. Results from Fumane, Isturitz, and Les Cottés. Archaeol. Anthropol. Sci. 10, 539–554. https://doi.org/10.1007/s12520-016-0365-5.

Falcucci, A., Conard, N.J., Peresani, M., 2020. Breaking through the aquitaine frame: a re-evaluation on the significance of regional variants during the Aurignacian as seen from a key record in southern Europe. Journal of Anthropological Sciences 98, 99–140. https://doi.org/10.4436/JASS.98021.

Falcucci, A., Karakostis, F.A., Göldner, D., Peresani, M., 2022. Bringing shape into focus: assessing differences between blades and bladelets and their technological significance in 3D form. J. Archaeol. Sci.: Report 43, 103490. https://doi.org/10.1016/j.jasrep.2022.103490.

Falcucci, A., Arrighi, S., Spagnolo, V., Rossini, M., Higgins, O.A., Muttillo, B., Martini, I., Crezzini, J., Boschin, F., Ronchitelli, A., Moroni, A., 2024a. A pre-Campanian Ignimbrite techno-cultural shift in the Aurignacian sequence of Grotta di Castelcivita, southern Italy. Sci. Rep. 14, 12783. https://doi.org/10.1038/s41598-024-59896-6.

Falcucci, A., Giusti, D., Zangrossi, F., De Lorenzi, M., Ceregatti, L., Peresani, M., 2024b. Refitting the context: a reconsideration of cultural change among early Homo sapiens at Fumane Cave through blade break connections, spatial taphonomy, and lithic technology. Journal of Paleolithic Archaeology. https://doi.org/10.1007/s41982-024-00203-0.

Falcucci, A., Bertola, S., Parise, M., Rio, M.D., Riel-Salvatore, J., Negrino, F., 2025a. A crossroads between the Mediterranean and the alps: lithic technology, raw material procurement, and mobility in the Aurignacian of Riparo Bombrini. J. Anthropol. Archaeol. 79, 101705. https://doi.org/10.1016/j.jaa.2025.101705.

Falcucci, A., Kitagawa, K., Doyon, L., Tassoni, L., Higham, T., Dominici, C., Dreossi, D., Crezzini, J., Rossini, M., Benazzi, S., Martini, I., Boschin, F., Spagnolo, V., Moroni, A., 2025b. Research Compendium for 'Revisiting the Early Aurignacian in Italy: new Insights from Grotta della Cala' (0.2). Zenodo. https://doi.org/10.5281/zenodo.15430431 [Data set].

Fiocchi, C., 1998. Contributo alla conoscenza del comportamento simbolico di Homo sapiens sapiens. Le Conchiglie Marine Nei Siti Del Paleolitico Superiore Europeo: Strategie Di Approvvigionamento, Reti Di Scambio, Utilizzo. Universities of Bologna, Ferrara and Parma, Italy.

Frouin, M., Douka, K., Dave, A.K., Schwenninger, J.-L., Mercier, N., Murray, A.S., Santaniello, F., Boschian, G., Grimaldi, S., Higham, T., 2022. A refined chronology for the middle and early upper Paleolithic sequence of riparo Mochi (Liguria, Italy). J. Hum. Evol. 169, 103211. https://doi.org/10.1016/j.jhevol.2022.103211.

Gambassini, P., 1997. Il Paleolitico Di Castelcivita: Culture E Ambiente. Electa, Naples.

Giaccio, B., Isaia, R., Fedele, F.G., Di Canzio, E., Hoffecker, J., Ronchitelli, A., Sinitsyn, A. A., Anikovich, M., Lisitsyn, S.N., Popov, V.V., 2008. The Campanian Ignimbrite and Codola tephra layers: two temporal/stratigraphic markers for the Early Upper Palaeolithic in southern Italy and eastern Europe. J. Volcanol. Geoth. Res. 177, 208–226. https://doi.org/10.1016/j.jvolgeores.2007.10.007.

Giaccio, B., Hajdas, I., Isaia, R., Deino, A., Nomade, S., 2017. High-precision 14C and 40Ar/39Ar dating of the Campanian Ignimbrite (Y-5) reconciles the time-scales of climatic-cultural processes at 40 ka. Sci. Rep. 7, 45940. https://doi.org/10.1038/srep45940.

Göldner, D., Karakostis, F.A., Falcucci, A., 2022. Practical and technical aspects for the 3D scanning of lithic artefacts using micro-computed tomography techniques and laser light scanners for subsequent geometric morphometric analysis. Introducing the StyroStone protocol. PLoS One 17, e0267163. https://doi.org/10.1371/journal.pone.0267163.

Grimaldi, S., Porraz, G., Santaniello, F., 2014. Raw material procurement and land use in the northern Mediterranean Arc: insight from the first Proto-Aurignacian of Riparo Mochi (Balzi Rossi, Italy). Quartar 61, 113–127. https://doi.org/10.7485/QU61_06.

Grosman, L., Muller, A., Dag, I., Goldgeier, H., Harush, O., Herzlinger, G., Nebenhaus, K., Valetta, F., Yashuv, T., Dick, N., 2022. Artifact3-D: new software for accurate, objective and efficient 3D analysis and documentation of archaeological artifacts. PLoS One 17, e0268401. https://doi.org/10.1371/journal.pone.0268401.

Gutiérrez-Zugasti, F.I., 2011. Shell fragmentation as a tool for quantification and identification of taphonomic processes in archaeomalacological analysis: the case of the cantabrian region (northern Spain). Archaeometry 53, 614–630. https://doi.org/10.1111/j.1475-4754.2010.00561.x.

Hahn, J., 1988. Die Geißenklösterle-Höhle Im Achtal Bei Blaubeuren I : Fundhorizontbildung Und Besiedlung Im Mittelpaläolithikum Und Im Aurignacien. Konrad Theiss Verlag, Stuttgart.

Heaton, T.J., Köhler, P., Butzin, M., Bard, E., Reimer, R.W., Austin, W.E.N., Bronk Ramsey, C., Grootes, P.M., Hughen, K.A., Kromer, B., Reimer, P.J., Adkins, J., Burke, A., Cook, M.S., Olsen, J., Skinner, L.C., 2020. Marine20—The marine radiocarbon Age calibration curve (0–55,000 cal BP). Radiocarbon 62, 779–820. https://doi.org/10.1017/RDC.2020.68.

Hedges, R.E.M., Pettitt, P.B., Bronk Ramsey, C., al, e., 1998. Radiocarbon dates from the Oxford AMS System: archaeometry datelist 26. Archaeometry 40, 437–455.

Higham, T., Brock, F., Peresani, M., Broglio, A., Wood, R., Douka, K., 2009. Problems with radiocarbon dating the Middle to Upper Palaeolithic transition in Italy. Quat. Sci. Rev. 28, 1257–1267. https://doi.org/10.1016/j.quascirev.2008.12.018.

Higham, T., Frouin, M., Douka, K., Ronchitelli, A., Boscato, P., Benazzi, S., Crezzini, J., Spagnolo, V., McCarty, M., Marciani, G., Falcucci, A., Rossini, M., Arrighi, S., Dominici, C., Devièse, T., Schwenninger, J.-L., Martini, I., Moroni, A., Boschin, F., 2024. Chronometric data and stratigraphic evidence support discontinuity between Neanderthals and early Homo sapiens in the Italian Peninsula. Nat. Commun. 15, 8016. https://doi.org/10.1038/s41467-024-51546-9.

Holm, S., 1979. A simple sequentially rejective multiple test procedure. Scandinavian Journal of Statistics, Theory and Applications 6, 65–70.

Holt, B., Negrino, F., Riel-Salvatore, J., Formicola, V., Arellano, A., Arobba, D., Boschian, G., Churchill, S.E., Cristiani, E., Di Canzio, E., Vicino, G., 2019. The Middle-Upper Paleolithic transition in Northwest Italy: new evidence from Riparo Bombrini (Balzi Rossi, Liguria, Italy). Quat. Int. 508, 142–152. https://doi.org/10.1016/j.quaint.2018.11.032.

Inizan, M.L., Reduron, M., Roche, H., Tixier, J., 1995. Technologie de la pierre taillée. In: Préhistoire De La Pierre Taillée, Tome 4. CREP, Meudon.

Kitagawa, K., Conard, N.J., 2020. Split-based points from the Swabian Jura highlight Aurignacian regional signatures. PLoS One 15, e0239865. https://doi.org/10.1371/journal.pone.0239865.

Kolobova, K.A., Krivoshapkin, A.I., Pavlenok, K.K., 2014. Carinated pieces in Paleolithic assemblages of central Asia1. Archaeol. Ethnol. Anthropol. Eurasia 42, 13–29. https://doi.org/10.1016/j.aeae.2015.06.003.

Kuhn, S.L., 2021. The Evolution of Paleolithic Technologies. Routledge, Oxon and New York.

Kuhn, S.L., Shimelmitz, R., 2022. From hafting to retooling: miniaturization as tolerance control in Paleolithic and Neolithic blade production. J. Archaeol. Method Theor. https://doi.org/10.1007/s10816-022-09575-5.

Kuhn, S.L., Stiner, M.C., 1998. The earliest Aurignacian of Riparo Mochi (Liguria, Italy). Curr. Anthropol. 39, 175–189. https://doi.org/10.1086/204694.

Kuhn, S.L., Stiner, M.C., Reese, D.S., Güleç, E., 2001. Ornaments of the earliest Upper Paleolithic: new insights from the Levant. Proc. Natl. Acad. Sci. 98, 7641–7646. https://doi.org/10.1073/pnas.121590798.

Kuhn, S.L., Stiner, M.C., Gulec, E., Ozer, I., Yilmaz, H., Baykara, I., Acikkol, A., Goldberg, P., Molina, K.M., Unay, E., Suata-Alpaslan, F., 2009. The early upper Paleolithic occupations at ucagizli cave (Hatay, Turkey). J. Hum. Evol. 56, 87–113. https://doi.org/10.1016/j.jhevol.2008.07.014.

Laplace, G., 1977. Il Riparo Mochi Ai Balzi Rossi Di Grimaldi (Scavi 1939-1949). Les Industries Leptolithiques, 32. Rivista di Scienze Preistoriche, pp. 3–131.

Lartet, É., 1860. Sur l'ancienneté géologique de l'espèce humaine en Europe occidentale. Annales des sciences naturelles 14, 117.

Le Brun-Ricalens, F., 2005. Chronique d'une reconnaissance attendue. Outils "carénés", outils "nucléiformes": nucléus à lamelles. Bilan après un siècle de recherches typologiques, technologiques et tracéologiques. In: Le Brun-Ricalens, F. (Ed.), Productions Lamellaires Attribuées À L'Aurignacien. MNHA, Luxembourg.

Le Brun-Ricalens, F., Bordes, J.-G., 2007. Les débuts de l'Aurignacien en Europe Occidentale: unité ou diversité? Du territoire de subsistance au territoire culturel. In: Floss, H., Rouquerol, N. (Eds.), Les Chemins De L'Art Aurignacien En Europe. Das Aurignacien Und Die Anfänge Der Kunst in Europa. Musée-Forum Aurignac, Aurignac.

Le Brun-Ricalens, F., Bordes, J.G., Bon, F., 2005. Productions Lamellaires Attribuées À L'Aurignacien. MNHA, Luxembourg.

Lê, S., Josse, J., Husson, F., 2008. FactoMineR: an R package for multivariate analysis. J. Stat. Software 25, 1–18. https://doi.org/10.18637/jss.v025.i01.

Leplongeon, A., Ménard, C., Bonhomme, V., Bortolini, E., 2020. Backed pieces and their variability in the later stone age of The Horn of Africa. Afr. Archaeol. Rev. 37, 437–468. https://doi.org/10.1007/s10437-020-09401-x.

Liolios, D., 2006. Reflections on the role of bone tools in the definition of the Early Aurignacian. In: Bar-Josef, O., Zilhao, J. (Eds.), Towards a Definition of the Aurignacian, 45. IPA, Lisbon, pp. 37–51.

Lombao, D., Falcucci, A., Moos, E., Peresani, M., 2023. Unravelling technological behaviors through core reduction intensity. The case of the early Protoaurignacian assemblage from Fumane Cave. J. Archaeol. Sci. 160, 105889. https://doi.org/10.1016/j.jas.2023.105889.

Mancini, L., Dreossi, D., Fava, C., Sodini, N., Tromba, G., Faretto, S., Montanari, F., 2007. TOMOLAB, the new X-ray microtomography facility @ELETTRA. Elettra Highlights 6, 128–129.

Marciani, G., Ronchitelli, A., Arrighi, S., Badino, F., Bortolini, E., Boscato, P., Boschin, F., Crezzini, J., Delpiano, D., Falcucci, A., Figus, C., Lugli, F., Oxilia, G., Romandini, M., Riel-Salvatore, J., Negrino, F., Peresani, M., Spinapolice, E.E., Moroni, A., Benazzi, S., 2020. Lithic techno-complexes in Italy from 50 to 39 thousand years BP: an overview of lithic technological changes across the Middle-Upper Palaeolithic boundary. Quat. Int. 551, 123–149. https://doi.org/10.1016/j.quaint.2019.11.005.

Marín-Arroyo, A.B., Terlato, G., Vidal-Cordasco, M., Peresani, M., 2023. Subsistence of early anatomically modern humans in Europe as evidenced in the Protoaurignacian occupations of Fumane Cave, Italy. Sci. Rep. 13, 3788. https://doi.org/10.1038/s41598-023-30059-3.

Martini, F., Beccaro, P., Ghinassi, M., Martino, G., 2003. Le materie prime delle industrie litiche del Paleolitico superiore e del Mesolitico di Grotta della Serratura (Marina di Camerota). Prima caratterizzazione degli areali e delle modalità di raccolta. Rivista di Scienze Preistoriche 53, 163–191.

Martini, I., Ronchitelli, A., Arrighi, S., Capecchi, G., Ricci, S., Scaramucci, S., Spagnolo, V., Gambassini, P., Moroni, A., 2018. Cave clastic sediments as a tool for refining the study of human occupation of prehistoric sites: insights from the cave site of La Cala (Cilento, southern Italy). J. Quat. Sci. 33, 586–596. https://doi.org/10.1002/jqs.3038.

Martini, I., Baucon, A., Boschin, F., 2021. Depositional processes and environmental settings in rock shelters: the case of the prehistoric Oscurusciuto site (Southern Italy). Geol. Mag. 158, 891–904. https://doi.org/10.1017/s0016756820001041.

Mellars, P., 2004. Neanderthals and the modern human colonization of Europe. Nature 432, 461–465.

Moreau, L., Odar, B., Higham, T., Horvat, A., Pirkmajer, D., Turk, P., 2015. Reassessing the Aurignacian of Slovenia: Techno-economic behaviour and direct dating of osseous projectile points. J. Hum. Evol. 78, 158–180. https://doi.org/10.1016/j.jhevol.2014.09.007.

Moroni, A., Boscato, P., Ronchitelli, A., 2013. What roots for the Uluzzian? Modern behaviour in Central-Southern Italy and hypotheses on AMH dispersal routes. Quat. Int. 316, 27–44. https://doi.org/10.1016/j.quaint.2012.10.051.

Moroni, A., Boscato, P., Allevato, E., Benocci, A., Di Bella, F., Pasquale, G.D., Favilli, L., Manganelli, G., Gambassini, P., 2016. The Mesolithic occupation at Grotta della Cala (Marina di Camerota- Salerno - Italy). A preliminary assessment. Preistoria Alp. 48, 171–182.

Moroni, A., Ronchitelli, A., Arrighi, S., Aureli, D., Bailey, S., Boscato, P., Boschin, F., Capecchi, G., Crezzini, J., Douka, K., Marciani, G., Panetta, D., Ranaldo, F.S.R., Scaramucci, S., Spagnolo, V., Benazzi, S., Gambassini, P., 2018. Grotta del Cavallo (Apulia – Southern Italy). The Uluzzian in the mirror. Journal of Anthropological Sciences 96, 1–36. https://doi.org/10.4436/jass.96004.

Mussi, M., 2002. Earliest Italy: an Overview of the Italian Paleolithic and Mesolithic. Springer, Boston.

Negrino, F., Riel-Salvatore, J., 2018. From neanderthals to anatomically modern humans in Liguria (Italy): the current state of knowledge. In: Borgia, V., Cristiani, E. (Eds.), Palaeolithic Italy. Advanced Studies on Early Human Adaptations in the Apennine Peninsula. Sidestone Press, Leiden, pp. 161–181.

Normand, C., 2006. L'Aurignacien de la salle de Saint-Martin (Grotte d'Isturitz, commune de Saint-Martin d'Arberoue, Pyrénéesatlantiques): donnés préliminaires sur l'industrie lithique recueillie lors des campagnes 2000–2002. In: Bon, F., Maíllo Fernández, J.M., Ortega-Cobos, D. (Eds.), Autour Des Concepts De Protoaurignacien, D'Aurignacien Archaïque, Initial Et Ancien. Unité Et Variabilité Des Comportements Techniques Des Premiers Groupes D'Hommes Modernes Dans Le Sud De La France Et Le Nord De L'Espagne. UNED, Madrid, pp. 145–174.

Odar, B., 2011. Archers at Potočka zijalka? Arheol. Vestn. 62, 443–456.

Odell, G.H., 2004. Lithic Analysis. Springer, New York.

Palma di Cesnola, A., 1989. L'Uluzzien: faciès Italien du Leptolithique archaïque. L'Anthropologie 93, 783–812.

Palma di Cesnola, A., 2001. Le Paléolithique Supérieur En Italie. Collection L'Homme dDs oOigines: Série "Préhistoire dDEurope, vol. 9. Editions Jérôme Millon, Grenoble.

Palma di Cesnola, A., 2004. Paglicci: L'Aurignaziano E Il Gravettiano Antico. Claudio Grenzi, Foggia.

Parow-Souchon, H., Belfer-Cohen, A., 2024. The use of carinated items in the Levantine Aurignacian—Insights from layer D, hayonim Cave, W. Galilee, Israel. PLoS One 19, e0301102. https://doi.org/10.1371/journal.pone.0301102.

Peresani, M., Cristiani, E., Romandini, M., 2016. The Uluzzian technology of Grotta di Fumane and its implication for reconstructing cultural dynamics in the Middle-Upper Palaeolithic transition of Western Eurasia. J. Hum. Evol. 91, 36–56. https://doi.org/10.1016/j.jhevol.2015.10.012.

Peresani, M., Forte, M., Quaggiotto, E., Colonese, A.C., Romandini, M., Cilli, C., Giacobini, G., 2019a. Marine and freshwater Shell exploitation in the early upper Paleolithic: Re-Examination of the assemblages from fumane Cave (NE Italy). PaleoAnthropology 2019, 64–81. https://doi.org/10.4207/PA.2019.ART124.

Peresani, M., Bertola, S., Delpiano, D., Benazzi, S., Romandini, M., 2019b. The Uluzzian in the north of Italy: insights around the new evidence at Riparo Broion. Archaeol. Anthropol. Sci. 11, 3503–3536. https://doi.org/10.1007/s12520-018-0770-z.

Perlès, C., 2018. Ornaments and other ambiguous artifacts from Franchthi vol 1(15). The Palaeolithic and the Mesolithic. Excavations at Franchthi Cave, Greece. Indiana University Press, Bloomington.

Pétillon, J.-M., 2006. Des Magdaléniens en armes. Technologie Des Armatures De Projectile En Bois De Cervidé Du Magdalénien Supérieur De La Grotte D'Isturitz (Pyrénées-Atlantiques).

Porraz, G., Simon, P., Pasquini, A., 2010. Identité technique et comportements économiques des groupes proto-aurignaciens à la grotte de l'Observatoire (principauté de Monaco). Gall. Prehist. 52, 33–59.

Posit team, 2023. Rstudio: Integrated Development Environment for R. Posit Software. PBC, Boston, MA.

R Core team, 2023. R: a Language and Environment for Statistical Computing. R Foundation for statistical computing, Vienna. https://www.R-project.org/.

Radmilli, A.M., 1977. Storia Dell'Abruzzo Dalle Origini All'Età Del Bronzo. Giardini, Pisa.

Reimer, P.J., Austin, W.E.N., Bard, E., Bayliss, A., Blackwell, P.G., Bronk Ramsey, C., Butzin, M., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kromer, B., Manning, S.W., Muscheler, R., Palmer, J.G., Pearson, C., van der Plicht, J., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Turney, C.S.M., Wacker, L., Adolphi, F., Büntgen, U., Capano, M., Fahrni, S.M., Fogtmann-Schulz, A., Friedrich, R., Köhler, P., Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Sakamoto, M., Sookdeo, A., Talamo, S., 2020. The IntCal20 Northern hemisphere radiocarbon Age calibration curve (0–55 cal kBP). Radiocarbon 62, 725–757. https://doi.org/10.1017/RDC.2020.41.

Riel-Salvatore, J., Negrino, F., 2018a. Human adaptations to climatic change in Liguria across the Middle–Upper Paleolithic transition. J. Quat. Sci. 33, 313–322. https://doi.org/10.1002/jqs.3005.

Riel-Salvatore, J., Negrino, F., 2018b. Proto-Aurignacian lithic technology, mobility, and human niche construction: a case study from Riparo Bombrini. In: Robinson, E., Sellet, F. (Eds.), Lithic Technological Organization and Paleoenvironmental Change. Springer, NY, pp. 163–187.

Rossini, M., Marciani, G., Arrighi, S., Pereira Santos, M.C., Spagnolo, V., Ronchitelli, A., Benazzi, S., Moroni, A., 2022. Less is more! Uluzzian technical behaviour at the cave site of Castelcivita (southern Italy). J. Archaeol. Sci.: Report 44, 103494. https://doi.org/10.1016/j.jasrep.2022.103494.

Rossini, M., Tomasso, A., Boschin, F., Martini, I., Crezzini, J., Dominici, C., Moroni, A., 2025. Early Epigravettian backed pieces from layer O of Grotta della Cala (Southern Italy). A techno-typological and use-wear integrated approach. J. Archaeol. Sci.: Report 62, 105046. https://doi.org/10.1016/j.jasrep.2025.105046.

Sala, B., 1983. Variations Climatiques Et Séquences Chronologiques Sur la Base Des Variations Des Associations Fauniques À Grands Mammifères, 38. Rivista di Scienze Preistoriche, pp. 161–180.

Sano, K., Arrighi, S., Stani, C., Aureli, D., Boschin, F., Fiore, I., Spagnolo, V., Ricci, S., Crezzini, J., Boscato, P., Gala, M., Tagliacozzo, A., Birarda, G., Vaccari, L., Ronchitelli, A., Moroni, A., Benazzi, S., 2019. The earliest evidence for mechanically delivered projectile weapons in Europe. Nature Ecology & Evolution 3, 1409–1414. https://doi.org/10.1038/s41559-019-0990-3.

Scerri, E.M.L., Drake, N.A., Jennings, R., Groucutt, H.S., 2014. Earliest evidence for the structure of Homo sapiens populations in Africa. Quat. Sci. Rev. 101, 207–216. https://doi.org/10.1016/j.quascirev.2014.07.019.

Schlager, S., 2017. Chapter 9 - morpho and rvcg – shape analysis in R: R-Packages for geometric morphometrics, shape analysis and surface manipulations. In: Zheng, G., Li, S., Székely, G. (Eds.), Statistical Shape and Deformation Analysis. Academic Press, pp. 217–256.

Schürch, B., Venditti, F., Wolf, S., Conard, N.J., 2021. Glycymeris molluscs in the context of the Upper Palaeolithic of Southwestern Germany. Quartar 68, 131–156.

Sigari, D., Zangrossi, F., Peresani, M., 2022. New ochre painted stones from the late ProtoAurignacian of Fumane Cave. Anthropologie (Brno) LX, 453–468. https://doi.org/10.26720/anthro.22.03.03.1.

Stiner, M.C., 1999. Palaeolithic mollusc exploitation at Riparo Mochi (Balzi Rossi, Italy): food and ornaments from the Aurignacian through Epigravettian. Antiquity 73, 735–754.

Stiner, M.C., 2010. Shell ornaments from the Upper Paleolithic through Mesolithic layers of Klissoura Cave 1 by Prosymna (Peloponnese, Greece). Eurasian Prehistory 7, 287–308.

Szmidt, C.C., Brou, L., Jaccottey, L., 2010. Direct radiocarbon (AMS) dating of split-based points from the (Proto)Aurignacian of Trou de la Mere Clochette, Northeastern France. Implications for the characterization of the Aurignacian and the timing of technical innovations in Europe. J. Archaeol. Sci. 37, 3320–3337. https://doi.org/10.1016/j.jas.2010.08.001.

Taborin, Y., 1993a. La Parure En Coquillage Au Paléolithique. CNRS Editions, Paris.

Taborin, Y., 1993b. Traces de façonnage et d'usage sur les coquillages perforés. In: Anderson, P.C., Beyries, S., Otte, M., et al. (Eds.), Traces Et Fonction. Les Gestes Retrouvés. Colloque International De Liège, 50. CRA et Université de Liège, ERAUL, pp. 255–267.

Tafelmaier, Y., 2017. Technological variability at the beginning of the Aurignacian in northern Spain. Implications for the Proto- and Early Aurignacian Distinction. Wissenschaftliche Schriften des Neanderthal Museums, Mettmann.

Tartar, E., 2012. The recognition of a new type of bone tools in early aurignacian assemblages: implications for understanding the appearance of osseous technology in Europe. J. Archaeol. Sci. 39, 2348–2360. https://doi.org/10.1016/j.jas.2012.02.003.

Tartar, E., White, R., 2013. The manufacture of Aurignacian split-based points: an experimental challenge. J. Archaeol. Sci. 40, 2723–2745. https://doi.org/10.1016/j.jas.2013.02.009.

Tassoni, L., 2019. Gli Ornamenti Su Conchiglia Dell'Uluzziano E Del Proto-Aurignaziano Delle Grotte Di Castelcivita E Della Cala (SA): Studio Tassonomico, Tafonomico E Sperimentale. University of Ferrara.

Tátá, F., Cascalheira, J., Marreiros, J., Pereira, T., Bicho, N., 2014. Shell bead production in the Upper Paleolithic of Vale Boi (SW Portugal): an experimental perspective. J. Archaeol. Sci. 42, 29–41. https://doi.org/10.1016/j.jas.2013.10.029.

Tejero, J.M., 2010. La explotación de las materias duras animales en el Paleolítico superior inicialaproximación tecno-económica a las producciones auriñacenses en la Península Ibérica. Ph.D. Dissertation, UNED. Universidad Nacional de Educación a Distancia.

Tejero, J.-M., 2014. Towards complexity in osseous raw material exploitation by the first anatomically modern humans in Europe: aurignacian antler working. J. Anthropol. Archaeol. 36, 72–92. https://doi.org/10.1016/j.jaa.2014.08.004.

Tejero, J.-M., Grimaldi, S., 2015. Assessing bone and antler exploitation at Riparo Mochi (Balzi Rossi, Italy): implications for the characterization of the Aurignacian in South-western Europe. J. Archaeol. Sci. 61, 59–77. https://doi.org/10.1016/j.jas.2015.05.003.

Teyssandier, N., 2023. Les débuts de l'Aurignacien dans leur cadre européen : où en est-on. Gall. Prehist. 63. https://doi.org/10.4000/galliap.4126.

Teyssandier, N., 2024. Us and them: how to reconcile archaeological and biological data at the middle-to-upper Palaeolithic transition in Europe? Journal of Paleolithic Archaeology 7, 1. https://doi.org/10.1007/s41982-023-00166-8.

Teyssandier, N., Zilhão, J., 2018. On the entity and antiquity of the aurignacian at Willendorf (Austria): implications for modern human emergence in Europe. Journal of Paleolithic Archaeology 1, 107–138. https://doi.org/10.1007/s41982-017-0004-4.

Vanhaeren, M., d'Errico, F., 2006. Aurignacian ethno-linguistic geography of Europe revealed by personal ornaments. J. Archaeol. Sci. 33, 1105–1128. https://doi.org/10.1016/j.jas.2005.11.017.

Villa, P., Pollarolo, L., Conforti, J., Marra, F., Biagioni, C., Degano, I., Lucejko, J.J., Tozzi, C., Pennacchioni, M., Zanchetta, G., Nicosia, C., Martini, M., Sibilia, E., Panzeri, L., 2018. From neandertals to modern humans: new data on the Uluzzian. PLoS One 13, e0196786. https://doi.org/10.1371/journal.pone.0196786.

Wood, R.E., Douka, K., Boscato, P., Haesaerts, P., Sinitsyn, A., Higham, T., 2012. Testing the ABOx-SC method: dating known-age charcoals associated with the Campanian Ignimbrite. Quat. Geochronol. 9, 16–26. https://doi.org/10.1016/j.quageo.2012.02.003.

Wood, R.E., Arrizabalaga, A., Camps, M., Fallon, S., Iriarte-Chiapusso, M.J., Jones, R., Maroto, J., de la Rasilla, M., Santamaria, D., Soler, J., Soler, N., Villaluenga, A., Higham, T., 2014. The chronology of the earliest Upper Palaeolithic in northern Iberia: new insights from L'Arbreda, Labeko Koba and La Viña. J. Hum. Evol. 69, 91–109. https://doi.org/10.1016/j.jhevol.2013.12.017.

Yeshurun, R., Doyon, L., Tejero, J.-M., Walter, R., Huber, H., Andrews, R., Kitagawa, K., 2024. Identification and quantification of projectile impact marks on bone: new experimental insights using osseous points. Archaeol. Anthropol. Sci. 16, 43. https://doi.org/10.1007/s12520-024-01944-3.