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A crossroads between the Mediterranean and the Alps: Lithic technology, raw material procurement, and mobility in the Aurignacian of Riparo Bombrini

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ABSTRACT

Riparo Bombrini is a collapsed rockshelter within the Balzi Rossi site complex, located at the intersection of the Maritime Alps, Northern Apennines, and Ligurian Sea. This unique environmental setting served as a crucial biogeographical corridor for human mobility along the Liguro-Provençal Arc during the Paleolithic. Multidisciplinary research at Bombrini identified three archaeological layers (i.e., A2, A1, and A0) overlying a semi-sterile Mousterian level. This paper explores the internal variability of the Protoaurignacian by analyzing lithic assemblages from layers A2 and A1, as well as a previously undescribed Early Aurignacian assemblage from layer A0. An analysis of assemblage integrity, lithic technology, and raw material procurement reveals distinct mobility and land-use strategies, despite technological uniformity. Remarkably, lithic production and use in both Protoaurignacian and Early Aurignacian layers frequently involved exogenous materials sourced from distances exceeding 150 km, with some reaching up to 450 km, spanning from the Rhône Valley to the Central Apennines. Variability in the procurement distance of discarded lithics and their changing reduction intensities highlight distinct patterns of logistical and residential mobility. Comparative analysis with regional sites indicates that foragers possessed sophisticated territorial knowledge, challenging the traditional view of the Protoaurignacian as the outcome of pioneering groups entering unfamiliar landscapes.

1. Introduction

Liguria is a geologically distinctive region, characterized by a mountain range that connects the Apennines to the Alps, forming a natural barrier between the Ligurian-Tyrrhenian and the Adriatic regions. The area's geomorphology is marked by steep, deeply incised valleys and limited coastal plains, which contribute to its rugged landscape (Negrino & Riel-Salvatore, 2018). This narrow coastal biogeographic corridor, often regarded as a preferential route for human and animal migration along the Liguro-Provençal Arc, has remained relatively unchanged during the Late Pleistocene (Grimaldi et al., 2014; Negrino et al., 2023; Pothier-Bouchard et al., 2024; Riel-Salvatore et al., 2022). In western Liguria, a prominent limestone cliff along the Tyrrhenian Sea forms the Balzi Rossi complex. The exceptional preservation of Pleistocene stratigraphic sequences here has made the cave systems opening into the Balzi Rossi cliff a focal point for past and ongoing archaeological research (Ryan et al., 2024). Key stratigraphic sites include Barma Grande, Grotta del Caviglione, Riparo Mochi, and Riparo Bombrini. While the majority of these sites were excavated in the past century using now outdated methods, excavations at the collapsed rockshelter of Bombrini have been conducted according to modern archaeological standards, continuing up until 2022 (Holt et al., 2019; Martin-Moya et al., 2020; Riel-Salvatore et al., 2023; Vallerand et al., 2024).

The multidisciplinary research at Bombrini has significantly contributed to our understanding of the transition from the Middle to the Upper Paleolithic (Negrino et al., 2023; Riel-Salvatore & Negrino, 2018a; Riel-Salvatore et al., 2022). One of the most distinctive features

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of Bombrini, and Liguria in general, is the absence of the Uluzzian industry, which typically appears between the Mousterian and Protoaurignacian (PA) (Palma di Cesnola, 1989). The Uluzzian is well-documented in central and southern Italy (Moroni et al., 2018; Rossini et al., 2022; Villa et al., 2018), as well as extending into northeastern Italy (Peresani et al., 2016; Peresani et al., 2019) and Greece (Koumouzelis et al., 2001; Starkovich, 2017). According to the most recent interpretations, the Uluzzian is considered an Upper Paleolithic technocomplex with no direct connections to the Mousterian, particularly in terms of subsistence strategies (Boscato & Crezzini, 2012), technological systems (Delpiano et al., 2024), and symbolic behaviors (Arrighi et al., 2020). Evidence from the Uluzzian sequence at Grotta del Cavallo in Apulia, where *Homo sapiens* (HS) teeth were discovered, suggests that the emergence of the Uluzzian may have been linked to a demographic shift in some regions of Italy (Benazzi et al., 2011; Moroni et al., 2018; but see Zilhão et al., 2015).

Despite the absence of the Uluzzian in Liguria, the discovery of a semi-sterile Mousterian layer beneath the PA at Bombrini is particularly relevant to this discussion (Riel-Salvatore et al., 2022). This finding suggests that Neanderthal presence in the region was limited prior to the onset of the Upper Paleolithic, a view recently reiterated by Higham et al. (2024). The PA is also associated with HS in Italy. At both Bombrini and Fumane Cave, two HS deciduous teeth were found in association with assemblages attributed to the PA (Benazzi et al., 2015). While no human remains have been recovered from other PA sites, the strong techno-typological similarities across assemblages have led archaeologists to confirm that the PA emerged as the result of a successive and possibly more successful dispersal of HS across Europe, beginning about 43–42 ky cal BP (Frouin et al., 2022; Hublin, 2015).

In addition to its significance in discussions of HS dispersal across Europe, the strategic location of Bombrini offers a unique opportunity to examine the role and extent of mobility among PA foraging groups, as well as their techno-cultural connections along the biogeographic corridor of the Liguro-Provençal Arc. At Bombrini, Mochi, and Grotte de l'Observatoire, the identification of raw materials sourced from over 200 km away—from the Rhône Valley in southeastern France to the central Apennines in Italy—points to significant mobility dynamics and cultural connections. Most researchers have linked these materials to direct procurement events as part of the mobility strategies employed by these groups, although the possibility of exchanging valuable raw materials between groups settled in adjacent regions cannot be excluded (Bertola et al., 2013; Grimaldi et al., 2014; Porraz et al., 2010; Riel-Salvatore & Negrino, 2018b). This stands in contrast to evidence from other PA sites, such as Fumane, where nearly all raw materials were sourced locally, though of high quality (Bertola, 2001; Falcucci et al., 2017).

The identification of two distinct archaeological layers, coupled with the high variability in raw materials, makes Bombrini one of the few sites where lithic analysis allows for detailed investigations of the mobility strategies employed by PA foraging groups. This is crucial for advancing beyond the long-standing debates surrounding cultural taxonomy (Falcucci et al., 2020; Tafelmaier, 2017; Teyssandier, 2023), which have hindered a more comprehensive understanding of the Aurignacian technocomplex. This focus on mobility is the central direction of recent research at Bombrini (Riel-Salvatore, 2010; Riel-Salvatore & Negrino, 2018b). One of the key findings is the identification of shifts in mobility strategies during the PA, despite the overall technological stability. This conclusion was recently supported by the analysis of faunal remains (Pothier-Bouchard et al., 2020; Pothier-Bouchard et al., 2024) and the spatial organization of the site (Vallerand et al., 2024), which reveal behavioral variability within the PA that remains underexplored at other sites.

Discussions on mobility in the Paleolithic have evolved from the pioneering studies of Binford (1980), followed by works from Kelly (2013) and Bettinger et al. (2015), who demonstrated that mobility in sub-contemporaneous forager societies is based on a fluid set of behaviors within the so-called forager-collector conceptual continuum (Riel-Salvatore & Barton, 2004). Foragers typically engage in residential mobility, moving the entire group to subsistence resources, while collectors rely on logistical mobility, where a small part of the group carries out procurement forays and brings resources back to a base camp. This results in collectors moving their base camps less frequently compared to foragers.

While this model has sometimes been applied too rigidly in past studies, scholars have shown that it should be considered a flexible theoretical framework to assess trends in human mobility, as observed in the Pleistocene archives of many cave sites (see Binford, 2001; Kuhn, 1995). It is important to note that the formation of these archaeological deposits does not reflect single occupational events but rather the accumulation of multiple occupations (i.e., palimpsests) that are nearly impossible to disentangle, thus representing time-averaged behaviors (Vallerand et al., 2024). However, scholars have demonstrated that this approach can yield meaningful insights into behavioral trends in the Aurignacian, when applied to both caves with reliable stratigraphic sequence and the rare open-air sites (Anderson et al., 2018; Blades, 1999a; Blades, 1999b; Chu et al., 2022; Riel-Salvatore & Negrino, 2018b).

This renewed focus on mobility and on the internal variability of the PA also has had larger implications for the anthropological study of these populations. First, it broadens the range of archaeological examples of hunter-gatherer societies that can help test and contextualize observations and the breadth of adaptations derived principally from ethnographic observations on sub-recent forager groups (Binford, 2001; Guenther, 2007; Pargeter et al., 2016; Wobst, 1978). Second, by highlighting the importance of mobility as a vector of internal dynamism among the PA, this developing agenda of research also favors the integration of multiple lines of evidence, such as lithic raw material and ornamental shell procurement strategies, to develop more integrated perspectives on PA adaptations and social networks.

Thus, in this study, we aim to build upon previous research conducted at Bombrini to further explore the behavioral variability across the two PA layers, and to contextualize the technological data within other Aurignacian sequences along the Mediterranean. The recently completed excavations will enable us to test earlier findings using the full set of lithics recovered, providing a more up-to-date discussion. The techno-typological analysis will be supplemented by the classification of lithics based on the estimated distance from which raw materials were collected. We will quantify several technological parameters, including reduction intensity and raw material provenance, to infer the mobility strategies employed by foraging groups during the formation of the PA. Prior to these analyses, we will apply the laminar break connection method by Bordes (2000) to assess the stratigraphic and spatial integrity of the PA at Bombrini. Finally, we will present, for the first time, data from the uppermost layer A0. Based on its techno-typological features, this layer can be attributed to the Early Aurignacian, aligning the sequence at Bombrini with nearby sites such as Mochi and Observatoire. Our studyincludes a detailed techno-typological dataset (Falcucci et al., 2025b) and an open-access repository of lithic 3D meshes (Falcucci et al., 2025a), following Open Science principles.

2. Riparo Bombrini

Riparo Bombrini (43°46′59.6″N, 07°32′7.6″E) is a collapsed rockshelter (with "Riparo" meaning rockshelter in Italian) of the Balzi Rossi complex (Fig. 1a). The site may have represented the eastern terminus of a large talus extending towards the sea from the entrance of Grotta del Caviglione (Riel-Salvatore & Negrino, 2018b). However, due to both historical and geological reasons, these archaeological deposits have always been treated as separate sites. Scientific exploration of Bombrini began in 1938, when Cardini identified a hearth and several lithic artifacts, which were attributed to the Aurignacian *sensu lato*. Systematic excavations were then conducted by G. Vicino in 1976 and between

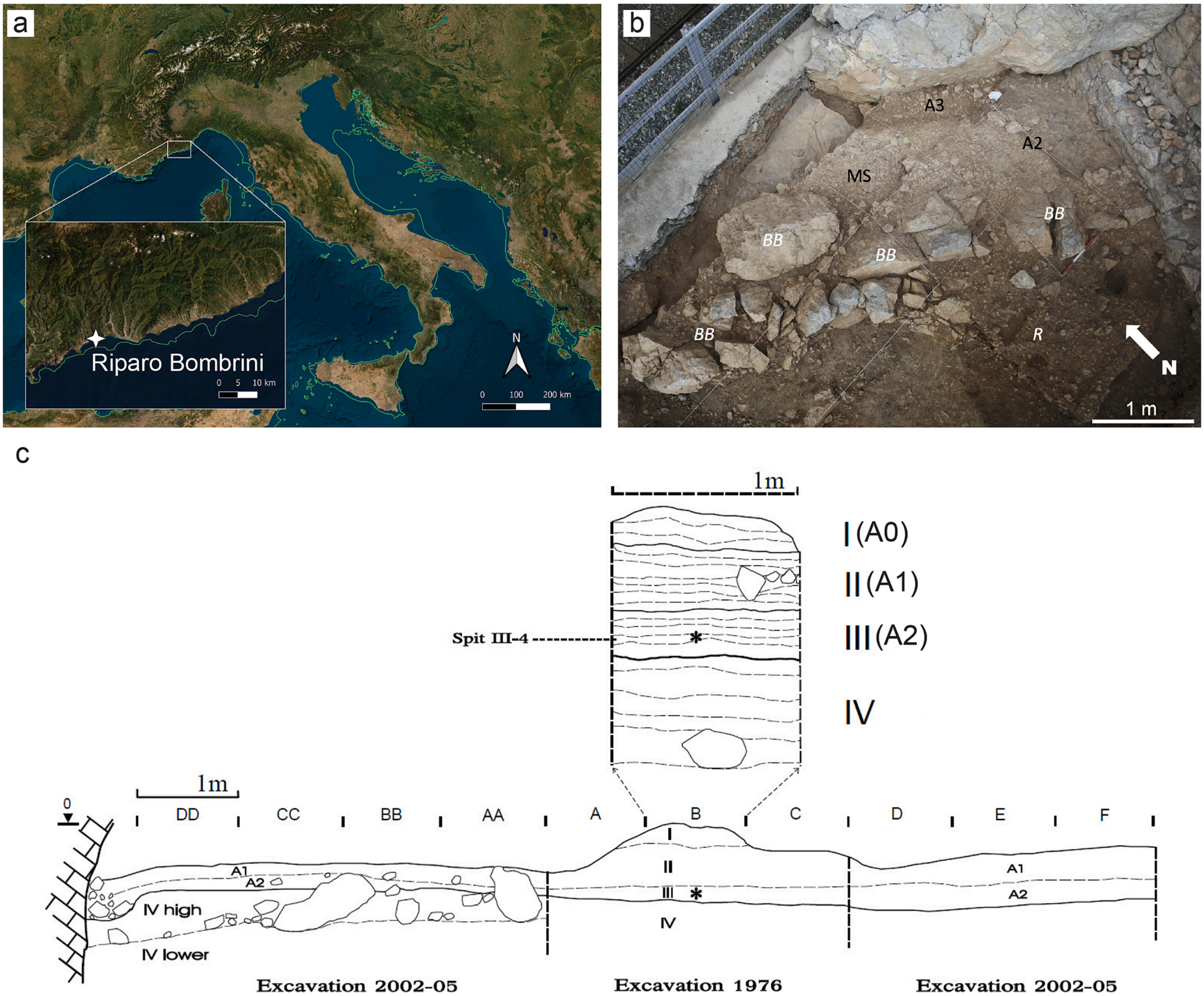

Fig. 1. Riparo Bombrini. (a) Map highlighting the location of the site in Liguria, northwestern Italy. The map includes a green line representing the reconstructed mean sea level at −65 m above the current sea level, using the Paleocoastlines GIS dataset (https://crc806db.uni-koeln.de/dataset/show/paleocoastlines-gis-dataset1462293239/); (b) Stratigraphic situation during the 2016 field season. The limestone wall of the shelter is visible, truncated on the left by the Genoa-Marseille railway line. The stratigraphic units A2 and A3, associated with the Protoaurignacian (PA), and the underlying Mousterian unit (MS), along with the breakdown blocks (BB) chronologically linked to it, are indicated. Modern reworked deposits (R) are visible on the right; (c) Stratigraphic sequence of Riparo Bombrini based on the 2002–2005 and 1976 excavations. The star marks the position of the human incisor in layer A2. Stratigraphic Unit I from Vicino's excavations corresponds to layer A0. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2002 and 2005 by one of us and B. Holt (Holt et al., 2019). Excavations resumed in 2015 under the scientific direction of F. Negrino and J. Riel-Salvatore, with the last fieldwork seasons focusing on expanding the area excavated by Vicino and collecting new samples for analysis using updated methodological approaches. The 2022 season marked the conclusion of the archaeological exploration at the site, which overall encompassed an area of about 30 m^2 (Riel-Salvatore et al., 2023).

Excavations at Bombrini have uncovered an important stratigraphic sequence (Fig. 1b, c), including Late Mousterian and PA deposits (Holt et al., 2019; Negrino & Riel-Salvatore, 2018; Negrino et al., 2023; Riel-Salvatore & Negrino, 2018b, a). The stratigraphic sequence is divided into three sedimentary macro-units: A0–A3, MS1–MS2, and M1–M7. The lowermost layers indicate Mousterian occupations dating to approximately 45–42 ky cal BP (Hirniak et al., 2020) and have yielded human remains attributed to Neanderthals (Riel-Salvatore et al., 2023). The most recent Mousterian layers, MS1 and MS2, date to ca. 42.75 ka cal BP and, though relatively scarce, represent one of the last Neandertal sites in Europe (Higham et al., 2014; Riel-Salvatore et al., 2022).

The excavations highlighted a rather marked discontinuity between the Mousterian and the PA layers, likely due to a possible erosional event, although it is believed that the human occupations at the site were not significantly separated by time (Negrino & Riel-Salvatore, 2018; Riel-Salvatore & Negrino, 2018a). The two main PA layers, A2 and A1, were found in sedimentary continuity. Radiocarbon dating suggests that A2 was deposited between 41.2 and 39.1 ky cal BP, encompassing Heinrich Event 4, while A1 was deposited between 38.3 and 35.9 ky cal BP, mostly during Greenland Interstadial 8 (GI8) (Benazzi et al., 2015; Negrino & Riel-Salvatore, 2018; Riel-Salvatore & Negrino, 2018b). Faunal evidence indicates a gradual warming from A2 to the top of A1. Equids and rhinoceroses, typically associated with colder, open environments, are found primarily in A2. Conversely, boars and roe deer, indicative of a more forested environment, are more frequent in A1, although conditions may still have been quite harsh, as suggested by the presence of ibex (Pothier-Bouchard et al., 2020).

The PA at Bombrini might have begun as early as in layer A3. However, the assemblage from this layer is minimal, making chronological and cultural assessments challenging. A3 was excavated only along a narrow 15 cm thick band of deposit along the shelter's wall. According to Riel-Salvatore & Negrino (2018b), A3 may correspond to the earliest PA occupations at the nearby Mochi, which dates between 43 and 42 ky cal BP (Douka et al., 2012; Frouin et al., 2022; Grimaldi et al., 2014).

Layers A2 and A1 are characterized by yellowish clayey loam with abundant angular clasts and large blocks detached from the vault. These features suggest deposition under colder climatic conditions compared to the preceding Mousterian (Riel-Salvatore & Negrino, 2018a). Both A2 and A1 contain hearths near the shelter wall, and A1 also features a hearth outside the shelter (Vallerand et al., 2024). Spatial analysis indicates that these layers do not represent strict occupation floors but rather palimpsests of activity accumulated over thousands of years. Vallerand et al. (2024) observed that A2, characterized by a clear structuring into two main areas near the shelter wall, suggests long-term occupation and site structuring. In contrast, A1 appears less structured, possibly indicating shorter-term occupations. Faunal analysis supports this interpretation, showing greater site maintenance in A2 (Pothier-Bouchard et al., 2020). A1 and A2 were in a few cases excavated together as A1-A2 when a separation was not evident. On top of A1, a small pocket of sediment was found in a limited area of the Vicino excavation, referred to as stratigraphic unit I (see Fig. 1c). This layer, subsequently named A0, contains a very small, yet undescribed, lithic assemblage that will be presented in this paper. A radiocarbon date (S-EVA-30845, 29,660 ± 250) places layer A0 between 34,620 and 33,682 ky cal BP (95.4 % probability).

One of the most significant findings from the PA at Bombrini is a lower deciduous incisor from layer A2, which is one of the earliest HS specimens from the Aurignacian (Benazzi et al., 2015). In addition to thousands of lithics and bones, layers A2 and A1 include important artifacts such as perforated mollusk shells and ochre (Cavallo et al., 2023; Holt et al., 2019; Negrino & Riel-Salvatore, 2018). Over 2,600 shells were recovered, with at least 570 gastropod shells, 91 of which show deliberate perforation (Gazzo et al., 2025). Most of these shells belong to *Tritia pellucida* and *Homalopoma sanguineum* species (Gazzo et al., 2025; Holt et al., 2019). According to Gazzo et al. (2023), the gastropods were not collected for dietary purposes, while the majority of bivalves were used as food. The presence in layer A2 of rare examples of *Littorina obtusata* and *Littorina saxatilis* may indicate contacts or exchanges with regions located on the Atlantic (Gazzo et al., 2025). Other non-utilitarian objects include three bird bone diaphyses decorated with incisions, two belemnite fragments (i.e., fossil shells), one of which was engraved for suspension, and six steatite beads that appear to be in the process of being worked. The presence of steatite, sourced from the Apennine region (Bertola et al., 2013), provides additional data to support the existence of extensive mobility and/or trade networks extending several hundred kilometers from the site. Despite a few bone tools, including awl and needle fragments as well as pointed pieces, have been recovered, no antler tools are known at the site.

3. Materials and methods

3.1. The break connection study

Archaeological excavations at Bombrini employed a 1 m^2 grid system to plot the recovered artifacts. All sediments were dry- and wet-sieved to ensure the recovery of even the smallest artifacts. Modern techniques, including Structure from Motion photogrammetry and density analyses, were used to manage and analyze 3D data obtained from the excavation (Martin-Moya et al., 2020; Putzolu et al., 2023). In this favorable context, we conducted a break connection analysis following Bordes (2000) to evaluate the stratigraphic and spatial integrity of the PA lithic assemblages.

One of the authors (MP) isolated all laminar fragments larger than 10 mm in maximum linear dimension (n = 1,516) from layers A1, A2, and the transition layer A1–A2 (Table 1). Layers A0 and A3 were excluded due to their very low artifact counts. The number of fragments is higher in A2 compared to A1, with only a limited number from the A1-A2 transition layer. Unlike previous studies focusing on blade fragments (Bordes, 2000; Falcucci et al., 2024b; Tsanova, 2013), we included all bladelets (i.e., laminar blanks with widths below 12 mm) in our analysis. The number of blades at Bombrini is relatively low, making it impractical to base this method solely on this size class. Indeed, when we measured the maximum width of all laminar fragments from A1, 628 out of 687 fragments were 12 mm or less in width, while 59 were classifiable as blades, representing only 8.6 % of the total assemblage. It is important to note that we did not consider previously connected blade/lets, as they shared the same spatial location and were likely the result of unintentional breakage during excavation.

Laminar fragments were arranged on two large tables following the protocol outlined by Falcucci et al. (2024b). Materials were organized by layer and square of provenance, and further divided by preservation state (i.e., proximal, mesial, and distal) to facilitate the systematic search for break connections. Most fragments exhibited minimal cortical coverage, so we focused on raw material variability within the identified sub-groups. Proximal fragments were tested against mesial and distal fragments, mesial fragments were tested against mesial and distal fragments, and vice versa. At least 90 hours were dedicated to identifying connections, with each piece checked twice. The conjoining rate was calculated for the entire sample, based on the total number of fragments tested and those successfully connected (Cziesla, 1990), as follows:

$$\frac{\textit{Number of successfully connected fragments}}{\textit{Total number of fragments tested}} \times 100$$

3.2. Lithic assemblages

To thoroughly reconstruct blade and bladelet technologies and raw material use from layers A2, A1, and A0, we analyzed all cores and tools, regardless of their degree of fragmentation or class (Table 2). Materials labeled as A1-A2 were excluded, as this designation was used for materials that could not be reliably assigned to either A2 or A1. For blanks, our primary focus was on complete blades and bladelets, although we also included some fragmented blanks, particularly those related to initialization and maintenance operations, as they are crucial for understanding the core reduction processes involved in laminar production. In some cases, fragmented blanks previously classified as tools were incorporated into the dataset to ensure consistency and comprehensive artifact tracking. Statistical and comparative analyses were performed on layers A2 and A1, while layer A0, due to its limited sample size, is presented in a separate section of this paper.

In all lithic subsets, bladelets are the most abundant blank type analyzed (Fig. S1). This is consistent with our focus on laminar production during the Aurignacian and aligns with the prominent features of these assemblages as described in previous studies (Riel-Salvatore & Negrino, 2018b). It is important to note that we did not study the relatively abundant flake component, which mainly pertains to the knapping of local chert from the Ciotti conglomerate. Overall, the number of lithic artifacts is slightly lower in A1 compared to A2, which is consistent with the quantification of laminar fragments sorted for the break connection study. Importantly, the number of available cores has significantly increased compared to previous studies, which described only 1 core from A1 and 9 from A2 (e.g., Riel-Salvatore & Negrino, 2018b).

3.3. Raw material procurement analysis

The analysis of raw material (petrographic description and

Table 1
Number and percentages of Protoaurignacian laminar fragments identified at Riparo Bombrini (layers A2, A1, and A1-A2), categorized by breakage type (i.e., proximal, mesial, and distal).

Layer	Proximal, n	Proximal, %	Mesial, n	Mesial, %	Distal, n	Distal, %	Total, n
A1	287	41.8	200	29.1	200	29.1	687
A1-A2	12	54.5	4	18.2	6	27.3	22
A2	354	43.9	249	30.9	204	25.3	807
Total	**653**	**43.1**	**453**	**29.9**	**410**	**27.0**	**1,516**

Table 2
Quantification of the analyzed lithic assemblages from layers A2, A1, and A0, with percentages provided in brackets.

Layer	Blank	Core	Core-Tool	Pebble	Tool	Total
A0	24 (64.9 %)	3 (8.1 %)	2 (5.4 %)	1 (2.7 %)	7 (18.9 %)	37
A1	334 (60.6 %)	28 (5.1 %)	5 (0.9 %)	0 (0.0 %)	184 (33.4 %)	551
A2	362 (55.6 %)	36 (5.5 %)	2 (0.3 %)	0 (0.0 %)	251 (38.6 %)	651
Total	**720 (58.1 %)**	**67 (5.4 %)**	**9 (0.7 %)**	**1 (0.1 %)**	**442 (35.7 %)**	**1,239**

provenance), conducted by one of the authors (SB), is crucial for understanding behavioral variability at Bombrini. Previous studies have shown that the PA in the region is primarily characterized by the use of high-quality allochthonous cherts and radiolarites, sourced from a broad area extending from the Rhône Valley in southeastern France to the Marche region in Italy (Grimaldi et al., 2014; Porraz et al., 2010; Riel-Salvatore & Negrino, 2018b). Over the years, the lithic raw materials of the Liguro-Provençal Arc have been mapped by various research projects, with significant contributions from the CNRS–CEPAM and the *Musée d'Anthropologie Préhistorique de Monaco* (Binder, 1994; Binder, 1998; Porraz, 2005; Porraz and Negrino, 2007; Simon, 2007; Tomasso, 2014). To classify lithics according to their raw material formations and reconstruct procurement distances, we consulted published literature and atlases (Negrino and Starnini, 2003; Peresani et al., 2018; Porraz and Negrino, 2007; Tomasso, 2014; Tomasso et al., 2016; Tomasso & Porraz, 2016; Tomasso, 2018), regional geological guides (GGR, 1991, 1994), and reviewed the lithological collections from the *Dipartimento di Antichità, Filosofia, Storia* at the University of Genoa, the *Musée d'Anthropologie Préhistorique de Monaco* (Principality of Monaco), and the *CEPAM-Université Côte-d'Azur* in Nice, France. It is worth noting that several studies have already addressed raw material procurement strategies in the PA of the region, including work at Observatoire (Porraz et al., 2010), Bombrini (Riel-Salvatore & Negrino, 2018b), and Mochi (Grimaldi et al., 2014).

Lithic raw materials were classified based on specific petrographic features, analyzed both macroscopically and under a stereomicroscope (i.e., an Optika SZ series up to 45X with Moticam digital camera). Features such as color, texture, structure, fossils, abiotic grains, and minerals formed the basis for grouping the artifacts into several different raw material types (Bertola, 2012). The specific characteristics of each raw material type allowed the identification of geological formations and provenance areas. We classified lithics as local when they were collected within 50 km of the site. This group includes chert from the heterogeneous "Ciotti" conglomerate. This raw material can be found just a few meters from the Balzi Rossi cliff and among the detrital fragments transported to the sea collected within 5 km of the site (Negrino, 2003; Negrino & Starnini, 2003). Another local raw material is the Perinaldo chert, found approximately 20 to 30 km east of the site (Grimaldi et al., 2014). Non-local raw materials were categorized into three groups based on their approximate radial distance from the site: circum-local (50–100 km), distant (100–150 km), and very distant (over 150 km). The distant and very distant groups were further divided based on whether the materials were collected in modern-day southeastern France (Provence) or northern Italy (Maritime Alps, Southern Alps, and Northern Apennines). We summarize the classification and provenance of the lithic raw materials in Table 3.

Circum-local raw materials include rocks from eastern Provence (Lea, 2005; Binder et al., 2022; Porraz, 2005; Rossoni-Notter and Simon, 2016; Tomasso, 2014):

- Northern Var and eastern Provence Tertiary lacustrine/littoral cherts and silcretes;
- Grasse Prealps Jurassic cherts;
- Northern Var (Castellane Arch) Valanginien and Turonien cherts;
- Nice Arch Turonien cherts;
- Rhyolite from the Massif of Estèrel.

Distant and very distant French-side raw materials include cherts from western Provence and the Rhône Valley (references as above):

- Northwestern Provence Apt-Forcalquier Oligocene cherts;
- South Provence (Toulon) Aptian cherts;
- Northwestern Provence and Rhône Valley Vaucluse Barremien-Bedoulian cherts.

Distant and very distant Italian-side raw materials include cherts and radiolarites from the Northern Apennines and Lombardian/Venetian Prealps (Bertola, 2001, 2012, 2016; Bertola et al., 2013; Bertola et al., 2018; Cancellieri, 2016; Conforti, 2020; Negrino et al., 2016; Wierer and Bertola, 2016; Binder et al., 2022; Tomasso, 2014):

- Ligurian-Emilian-Tuscan red/green radiolarites (the so-called "Diaspri", Monte Alpe cherts formation);
- Emilian Calcari Selciferi Triassic/Jurassic cherts (Case Caldarola and similar complexes);
- Emilian Calcari Diasprigni Jurassic cherts (Case Caldarola and similar complexes);
- Emilian Maiolica upper Jurassic/lower Cretaceous cherts (Case Caldarola and similar complexes);
- Umbria-Marche Scaglia Rossa upper Cretaceous/Eocene cherts;
- Umbria-Marche Scaglia Variegata Eocene cherts;
- Lombardian/Venetian Prealps Maiolica upper Jurassic cherts.

The greatest distances reach ca. 450 km from the site (i.e., the Scaglia Rossa and Scaglia Variegata from the Umbrian-Marchean Apennine), as well as the unique finding (i.e., a sidescraper) of Maiolica chert from the Lombardian/Venetian Prealps (Negrino et al., 2016). Most artifacts listed in Table 2 were classified according to the procurement distance scheme, with only 55 artifacts (4.4 %) not securely assigned to a specific raw material type or formation and therefore classified as "Undetermined". Additionally, 25 artifacts (2 %) were excluded from the raw material procurement analysis due to difficulties in merging the technological and raw material datasets.

Table 3
List of raw material formations sorted according to the procurement distance groups used in this paper. The raw material formations are as follows: EACC (Emilian Apennine Case Caldarola Complex), EM (Esterel Massif), GP (Grasse Prealps), LEAP (Ligurian-Emilian Apennine), L/VP (Lombardian/Venetian Prealps), MA (Maritime Alps), NA (Nice Arch), NV (North Var), NWP (North Western Provence), SP (South Provence), and UMAP (Umbria-Marche Apennine).

Local (0–50 km)	Circum-Local (50–100 km)	Distant French (100–150 km)	Distant Italian (100–150 km)	Very distant French (over 150 km)	Very distant Italian (over 150 km)
Ciotti (MA); Perinaldo-Baiardo (MA)	Thitonian-Berriasian (GP); Valanginian (NV); Turonian (NV); Turonian (NA); Eocene (NA); Rhyolite (EM)	Oligocene Apt-Forcalquier (NWP); Aptian (SP)	Diaspri (LEAP)	Barremian-Bedoulian Vaucluse (NWP)	Calcari selciferi (EACC); Calcari Diasprigni (EACC); Maiolica (EACC); Scaglia Rossa (UMAP); Scaglia Variegata (UMAP); Maiolica (L/VP)

3.4. Lithic technology and reduction intensity

The goal of the lithic analysis was to describe the production of laminar implements in order to track technological and behavioral variability across the studied lithic assemblages. To achieve this, one of us (AF) focused on the production of laminar implements and used the raw material data to assess its role in the observed technological similarities and differences. All lithics listed in Table 2 were analyzed using a combination of attribute analysis (Andrefsky, 1998; Odell, 2004) and reduction sequence analysis (Inizan et al., 1995; Soressi & Geneste, 2011), following methodologies developed by one of us to study PA and Early Aurignacian sites across Italy (e.g., Falcucci et al., 2017; Falcucci et al., 2024a). We quantified a set of continuous and discrete attributes for individual lithics, including maximum linear dimension, platform dimensions and shapes, blanks' outline morphologies, degree of profile curvature and twisting, and scar pattern directions and orientations. Retouched blanks were classified using a simplified typological list developed by Demars & Laurent (1992). For laterally modified tools, we described the position and extent of the retouching.

To complement the technological analysis, we employed Elliptic Fourier Analysis (EFA) (Rohlf, 1990) to objectively quantify the morphological variability of complete bladelets in terms of blanks' outline shapes, assessing differences based on stratigraphic recovery and raw material provenance. The EFA was conducted using the *Momocs* R package (Bonhomme et al., 2014) and follows common approaches in lithic analysis (Falcucci et al., 2024a; Leplongeon et al., 2020; Matzig et al., 2021). To perform EFA, we extracted the 2D outline coordinates of the artifacts using the open-source software *DiaOutline* (Wishkerman & Hamilton, 2018). We explored the mean shape variability by conducting a non-parametric MANOVA (i.e., PERMANOVA), with 10,000 permutations, using the *vegan* package (Oksanen et al., 2022). Disparity tests (Guillerme, 2018) were then performed to quantify the sum of morphological variances within layers and raw materials, using the output from the principal component analysis (PCA), and bootstrapping the PCA data 1,000 times following Matzig et al. (2021).

For cores, several metric measurements were taken after orienting the artifact according to its technological axis, as described in Lombao et al. (2023). Cores were also classified based on the location and extent of the flaking surface, following the methodology outlined by Falcucci & Peresani (2018). Additionally, we described the shape of the striking platform and flaking directionality. We used 3D meshes to quantify the volume (in mm^3) and surface area (in mm^2) using the *Rvcg* R package (Schlager, 2017). The surface area measurement enabled us to apply the Scar Density Index (SDI) by Clarkson (2013) to measure reduction intensity across laminar cores. To do so, we counted all scars larger than 10 mm and divided the total core surface area by the total scar count. The SDI value was then logarithmically transformed to normalize the data distribution and reduce the influence of outliers.

Data exploration and statistical analyses were conducted using the R programming language (R Core team, 2023) in R Studio (Posit team, 2023). Datasets and scripts are available in an open-access repository on Zenodo (Falcucci et al., 2025b). All generated 3D meshes (n = 110) are also stored under the CC BY 4.0 license on Zenodo (Falcucci et al., 2025a).

4. Results

4.1. Break connections

The systematic search for laminar break connections resulted in only two successful conjoins. They comprise a total of four connected fragments, yielding an extremely low conjoining rate of just 0.3 %. The first conjoin involves a mesial and distal fragment of a blade made from circum-local French chert from layer A2, found near the hearth in the shelter interior. The second connection is between a mesial and distal fragment of distant Italian radiolarite from layer A1, discovered on the shelter dripline. In both cases, the connections are intra-layer, linking fragments from the same (Fig. 2a) or adjacent (Fig. 2b) squares, suggesting very limited horizontal and vertical movement.

4.2. Raw material procurement

The most commonly used raw material in layers A2 and A1 is chert, which accounts for approximately 90 % of the material in both layers (Table S1). Radiolarite is slightly more common in A2, but its overall frequency remains low (4.6 % in A2 and 2.7 % in A1). Volcanic, magmatic, and metamorphic rocks, as well as quartzarenites, were used infrequently. As expected, a significant number of artifacts can be attributed to distant sources, confirming the extensive radius of raw

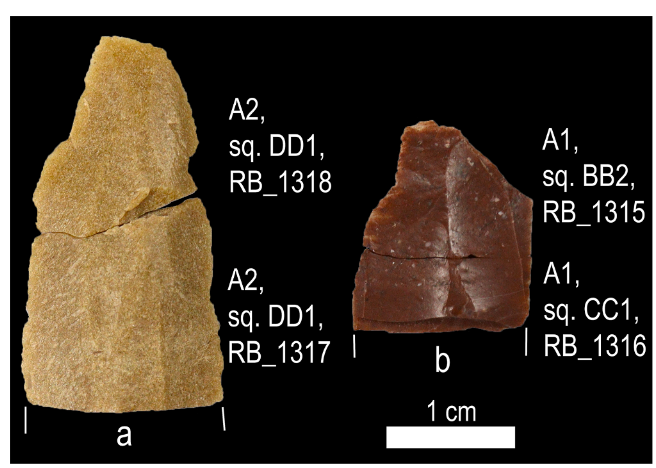

Fig. 2. Identified break connections. (a) Conjoin between two blade fragments from a circum-local French chert (layer A2), and (b) conjoin between two blade fragments from a distant Italian radiolarite (layer A1). The figure includes information on the square (sq.) and blanks' IDs (RB_1315, RB_1316, RB_1317, RB_1318) from the technological dataset. (Photos: A. Falcucci).

material procurement by the foraging groups visiting the site during the formation of both layers A1 and A2. In our dataset, only about 30 % of the raw materials are classified as local (Table S2). Interestingly, most non-local raw materials originate from the west (i.e., France), with similar proportions in both A1 (ca. 58 %) and A2 (ca. 51 %). Non-local raw materials from Italy are less represented in both A1 (11 %) and A2 (ca. 14 %).

The frequency of local raw materials is very low among retouched bladelets, with most tools made from distant and very distant cherts (Fig. 3a). There is, however, a slightly higher number of retouched bladelets made from local and circum-local materials in A2. This pattern is less pronounced when considering other tool types. Specifically, A1 shows a slightly higher proportion of local materials, while A2 contains more tools made from very distant sources (Fig. 3b). Among non-modified blanks, there is a greater number of local and circum-local materials among bladelets in A2, with a decrease in distant, but not very distant, bladelets (Fig. 3c). This pattern is even more pronounced when considering other blank types (Fig. 3d). Notably, the patterns identified among blanks do not align with those observed for cores. More local raw materials were found among laminar cores in A1, where circum-local materials are absent, and distant cores are less frequent (Fig. 3e). Interestingly, all flake cores from A1 are made from local materials (Fig. 3f). The percentage of local raw materials in flake cores is also high in A2, although a few cores are made from distant and very distant sources.

4.3. Core reduction procedures

The A2 and A1 lithic assemblages at Bombrini are characterized by the production of bladelets from volumetric platform cores. Several cores and their by-products have been discarded in both layers, providing essential data to understand core reduction strategies during the PA in northwestern Italy. Flake production was also a significant component of core reduction at the site (Table 4). Initial and tested cores are relatively uncommon, with A2 having slightly more tested cores than A1. The low number of lithics with cortical coverage greater than 66 % in both layers (Table S3) suggests that core decortication and preliminary testing primarily occurred outside the site. On the other hand, a few crested blanks indicate that core secondary initialization was carried out on-site. Crested blanks are present in both layers, with 12 artifacts in A1 and 11 in A2 (Table S4 and see Fig. 4). We also identified a few crested burin spalls, likely associated with the initialization of bladelet cores on flake blanks. Notably, blanks associated with core initialization are more frequently made from local materials in A1, whereas distant sources are more common in A2 (Table S5).

Cores have been further classified based on the last visible negatives at discard (Table 5). Cores with laminar negatives are more common in A1 and less frequently attested in A2, which is linked to the large number of flake cores in A2. Many of these flake cores can be classified as multidirectional and platform unidirectional cores. Laminar cores primarily display bladelet negatives (Fig. 5), with some flake negatives associated with maintenance operations. Blade negatives are only observed in one instance from A1. This particular core predominantly exhibits bladelet negatives, and the single blade scar likely served to maintain the core's convexity, as indicated by its position at the interface between the core's flaking surface and flank (Fig. 5h). This interpretation is further supported by the technological classification of the few unretouched blades, most of which are linked to core initialization and maintenance phases (Table S6). In contrast, tools made on blades mostly correspond to optimal reduction phases (Table S7).

The technological configuration of laminar cores suggests that toolmakers oriented the selected raw materials, both nodules and flakes, along their longitudinal morphological axis. Carinated technology is rare, with only a few cores falling into this category. One carinated core can further be classified as a carinated burin. All laminar cores exhibit predominantly unidirectional flaking, often with sub-parallel reduction patterns (Tables S8–S9). Striking platforms are consistently plain and sometimes reshaped by core tablets (Fig. 4a, am). The only bladelet cores with bidirectional removals are those reduced by bipolar knapping on anvil (e.g., Fig. 5e, n), likely applied during the final stages of core reduction to maximize blank production. Metric analysis of laminar cores confirms that bladelets were the primary production goal. Comparing the length of the flaking surfaces of laminar cores at discard with the length of complete blades and bladelets reveals a greater overlap between the size of the bladelets and the cores' flaking surfaces. In contrast, blades do not correspond in size to the length of the flaking surfaces at discard (Fig. S2).

4.4. Technological and metric features of the bladelets

The knapping technique used to detach bladelets is consistent across both assemblages, indicating the almost exclusive use of direct marginal percussion to produce thin and elongated blanks. The analysis of preserved platforms shows a high frequency of plain platforms, followed by linear and punctiform types (Table S10). Platform width and thickness values do not significantly differ between the two assemblages (Fig. S3). Bulbs are absent in more than 65 % of cases, and when present, they are only moderately developed (Table S11). Lips are generally moderately developed (Table S12).

As observed in the cores, the flaking directions visible on the dorsal side of the bladelets are predominantly unidirectional, with scars often following a sub-parallel orientation. Bidirectional removals are nearly absent (Table S13). Profile curvature data show that straight and slightly curved profiles dominate (Table S14), while profile twisting is minimal (Table S15). In terms of cross-sectional shape, bladelets are mostly triangular and trapezoidal (Table S16).

The metric analysis of non-modified bladelets shows that the knapping objectives were short and slender bladelets, with a median length of around 18 mm in both A1 and A2 (Table S17). There is no significant inter-layer variability in the distribution of length and thickness values, although bladelets from A1 appear to be slightly narrower (Fig. S4). However, this variation does not affect the overall morphology of the bladelets in terms of elongation (i.e., length-to-width ratio) and robustness (i.e., width-to-thickness ratio) (Fig. S5). Finally, we found that in A2, bladelets made from local or non-local raw materials are indistinguishable in terms of size (Fig. S6), whereas bladelets made from non-local raw materials are consistently smaller across all dimensions in A1 (Fig. 6).

4.5. Shape of unretouched bladelets

The first three components of the PCA on bladelet outlines explain 86 % of the variance in the dataset (Fig. S7). These components describe the degree of elongation (PC1), distal asymmetry (PC2), and distal convergence (PC3) of the bladelets (Fig. S8). PC1 shows an allometric signal, as evidenced by the Spearman's correlations with linear dimensions (Table S18). PC2 does not exhibit an allometric signal, whereas PC3 displays only a very weak signal. The PC1 to PC2 scatterplots in Fig. 7 reveal two key findings. First, bladelets from A2 and A1 are extremely similar in shape, with almost identical means (Fig. 7a). This is confirmed by the PERMANOVA on the first nine PCs (which explain 95 % of the variance), yielding an R2 of 0.00537 and a p-value of 0.12. Second, bladelets sorted by raw material provenance do not show marked differences in shape (Fig. 7b). Although the mean value of bladelets from local sources is slightly shifted toward the positive axis of PC1, indicating less elongated blanks, the differences are not statistically significant ($R^2 = 0.00994$, $p = 0.27$). Similarly, bladelets classified by geographic origin (south-east: Italy, west: France) do not differ significantly in shape ($R2 = 0.00695$, $p = 0.25$).

The shape disparity analysis reveals significant differences in the amount of total morphological variation when bladelets are sorted according to the combination of layer and raw material provenance

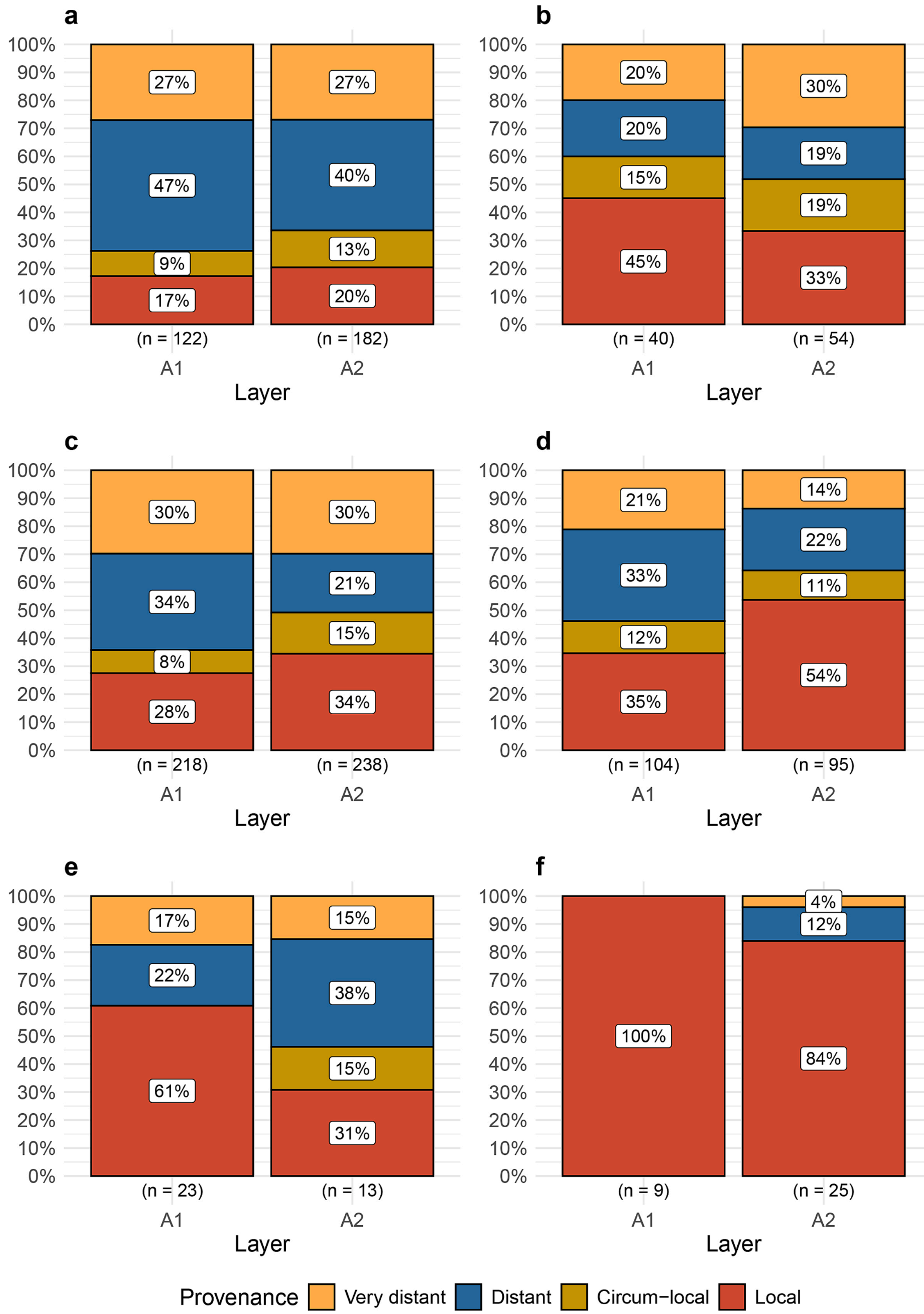

Fig. 3. Raw material procurement analysis. (a) Retouched bladelets; (b) other tools; (c) unmodified bladelets; (d) other unmodified blanks; (e) laminar cores; (f) non-laminar cores. The distribution of raw materials in each category is color-coded according to proximity: local, circum-local, distant, and very distant. Refer to the legend for color-coding details.

Table 4
Classification of cores from layers A2 and A1 based on technological features. The classification follows Falcucci & Peresani (2018), who consider the location and orientation of the flaking surface in relation to the striking platform(s). Rounded percentages are provided in brackets.

Classification	A1	A2	Total
Initial	2 (6 %)	2 (5 %)	4 (6 %)
Bipolar	2 (6 %)	1 (3 %)	3 (4 %)
Burin core	1 (3 %)	0 (0 %)	1 (1 %)
Carinated	3 (9 %)	2 (5 %)	5 (7 %)
Multi-platform	4 (12 %)	1 (3 %)	5 (7 %)
Narrow-sided	2 (6 %)	2 (5 %)	4 (6 %)
Semi-circumferential	4 (12 %)	3 (8 %)	7 (10 %)
Wide-faced flat	5 (15 %)	0 (0 %)	5 (7 %)
Multidirectional flake	2 (6 %)	14 (37 %)	16 (23 %)
Platform flake	4 (12 %)	5 (13 %)	9 (13 %)
Core shatter	3 (9 %)	5 (13 %)	8 (11 %)
Tested raw material	1 (3 %)	3 (8 %)	4 (6 %)
Total	**33**	**38**	**71**

categories. The boxplots in Fig. 8 display the overall sum of variance across the raw materials groups sorted according to local and non-local (i.e., circum-local, distant, very distant) provenance. Interestingly, bladelets from A1 made from non-local raw materials exhibit a higher disparity compared to local blanks from the same layer, as well as bladelets from A2 made from non-local materials. The disparity values are also higher for A2 bladelets from non-local sources, but these values are much lower than those from A1. All tested groups show significant differences based on the Wilcoxon tests.

4.6. Core reduction intensity

The SDI data indicate that reduction intensity across the core assemblage is partly linked to the distance of raw material sources, with values following a clear distance gradient (Fig. 9a). The core volume is strongly correlated with the logSDI index, showing good agreement between the overall size of the core and its intensity of reduction (Fig. 9b). The increased reduction intensity with distance is exemplified by three small, highly reduced bladelet cores that display evidence of bipolar reduction in the final stages of core reduction (see Fig. 9b). However, the degree of overlap across cores sorted by raw material provenance suggests that other factors also contribute to the observed variability. The SDI data shows that cores from A1 are generally more reduced than those from A2 (Fig. 9c). When cores are further sorted by local and non-local raw material sources, only the comparison between local materials is statistically significant (Fig. 9d). Overall, the increased reduction observed in the A1 assemblage is supported by other evidence, such as the higher proportion of multi-platform cores, suggesting core rotation to maximize blank production (Falcucci & Peresani, 2018), and the presence of several wide-faced cores, whose flattening is also linked to the degree of core reduction (Lombao et al., 2023).

4.7. Tool modification

At Bombrini, modified blanks are very common. Most tools are retouched bladelets, with percentages reaching nearly 80 % in both assemblages (Table 6). Flakes and blades with lateral retouching follow, along with endscrapers (Fig. 10). Burins are slightly less common than endscrapers. The composition of tool types does not differ significantly between the two assemblages ($X^2 = 14.543$, $p = 0.3$). Rare tool types include carinated endscrapers, thick-nosed endscrapers, and carinated burins. The second most common blanks selected for tools are flakes in both layers. Excluding bladelets, flakes account for 64 % of the tools in A1 and 58 % in A2. The number of blades is low but not negligible, with only slight inter-layer variations (Fig. S9).

The retouched bladelets from both layers A1 and A2 (Fig. 11) predominantly exhibit inverse retouching, with less frequent direct and alternate retouching (Table 7). Although there is a slight increase in direct retouching and a decrease in alternate retouching in A1, these differences are not statistically significant ($X^2 = 5.685$, $p = 0.1$). Most ventral retouching is positioned on the right side, with only about 4 % on the left side. Retouched bladelets typically show marginal modifications, rarely forming a 80/90-degree angle (e.g., Fig. 11*h*, k). Almost all retouched bladelets derive from the optimal phase of core reduction, with only one exhibiting more than 33 % cortex coverage (Table S19). This pattern also applies to blades, although slightly more tools on flakes show cortical coverage, particularly in layer A1 (Table S19). The dimensions of retouched bladelets show no significant differences in length, width, or thickness between the two layers (Fig. S10), consistent with the variability observed in unretouched bladelets.

4.8. The lithic assemblage from layer A0

Layer A0 contains a limited lithic assemblage. Nevertheless, the available blanks, cores, and tools reveal noteworthy trends. Similar to layers A2 and A1, non-local raw materials dominate, with very distant sources comprising 33.3 % ($n = 12$) and distant sources 30.6 % ($n = 11$) in our dataset (Table S20). Of the five cores found, two used for bladelet production are classified as carinated cores (Table S21), specifically a carinated endscraper (Fig. 12h) and a thick-nosed endscraper (Fig. 12i). The core shatter (Fig. 12g) and initial flake core (Fig. 12d) are made from local materials, while the thick-nosed endscraper and bipolar core (Fig. 12e) are from distant sources, and the carinated endscraper is made from circum-local material. The SDI data indicates that the bipolar core is the most reduced, while the core made from local raw material (excluding the core shatter) is the least reduced (Fig. S11). Based on visible laminar negatives on the bipolar core, it is likely that this core was used in the final stage of blank production following the freehand bladelet production. The final bladelet negatives on the carinated cores' flaking surfaces (measuring 13–16 mm in length) and the recovery of complete bladelets ($n = 8$) with a median length of 11.8 mm (Table S22 and Fig. 12f) suggest that the production targets were shorter bladelets compared to those from A2 and A1.

The tool category includes nine artifacts (Table S23), three of which are retouched bladelets made from very distant ($n = 1$) and distant ($n = 2$) sources, modified via direct ($n = 2$) and inverse retouching ($n = 1$). Other tools are made on both blades ($n = 3$) and flakes ($n = 3$), with only one (i.e., a scaled piece) made from local materials. A notable tool is a thick blade with direct bilateral retouch and two burin spalls removed from the edges (Fig. 12a) made from distant western Provence chert.

5. Discussion

5.1. Assessing assemblage and spatial integrity of the Protoaurignacian layers

Given the high variability in raw materials at Bombrini, the results of the systematic break connection search were unexpected. Several points of discussion arise from these findings. The only two connections identified relate to blades, which are the least common blank types at Bombrini. In contrast, no bladelet fragments were connected, despite their high number. In this regard, Bel et al. (2020) found that conjoining success decreases significantly when comparing small-sized artifacts, particularly those with narrower fractures, which reduce the area available for testing break connections. The reduced thickness of bladelets also suggests that these blanks fractured more easily, resulting in higher fragmentation and an increased number of potential connections. Furthermore, the technological composition of laminar implements at Bombrini may have hindered the search for connections, as very few cortical blades/lets were identified. For instance, at Fumane Cave, Falcucci et al. (2024b) were able to refit a large number of blades with cortical coverage, providing additional markers for identifying break connections. However, the technological and metric composition of the

Fig. 4. Blanks associated with the initialization, maintenance, and optimal core reduction phases. (a, am) Core tablets; (b, d, e, f, h, i, j, k, l, n, ab, ac, ad, ae, ah, ai, aj, ak, al, ao, ap, aq, ar, as, au) non-cortical bladelets; (c, p, q, r, z, aa) maintenance flakes; (g) semi-cortical bladelet; (m, aw) crested bladelets; (o, x, af, ag, an, at) lateral bladelets; (s, w, az) neo-crested bladelets; (t) lateral blade; (u) non-cortical blade; (v) cortical flake; (y) crested blade; (av, ax, ba) semi-cortical blades; (ay) second-crested blade. Blanks are sorted according to raw material provenance as follows: (a, b, l, v, am, an, ao, ay) circum-local french chert; (c, e, o, q, w, x, ab, af, ai, ar, aw, ba) distant french chert; (d, g, h, p, u, al, az) very distant french chert; (f, i, k, m, n, r, t, y, z, ah, aj, ap, at, av, ax) local chert; (j, s, ac, ae, ag, ak, aq) very distant italian chert; (aa, as, au) distant italian radiolarite; (ad) undetermined. The numbers following the letters correspond to the lithics' IDs as reported in the associated dataset (Photos: A. Falcucci).

Table 5
Classification of cores from layers A2 and A1 based on the last visible negatives on the flaking surfaces. Rounded percentages are provided in brackets.

Layer	Bladelet	Bladelet-Blade	Bladelet-Flake	Flake	Undetermined	Total
A1	17 (52 %)	1 (3 %)	5 (15 %)	7 (21 %)	3 (9 %)	33
A2	7 (18 %)	0 (0 %)	7 (18 %)	22 (58 %)	2 (5 %)	38
Total	**24 (34 %)**	**1 (1 %)**	**12 (17 %)**	**29 (41 %)**	**5 (7 %)**	**71**

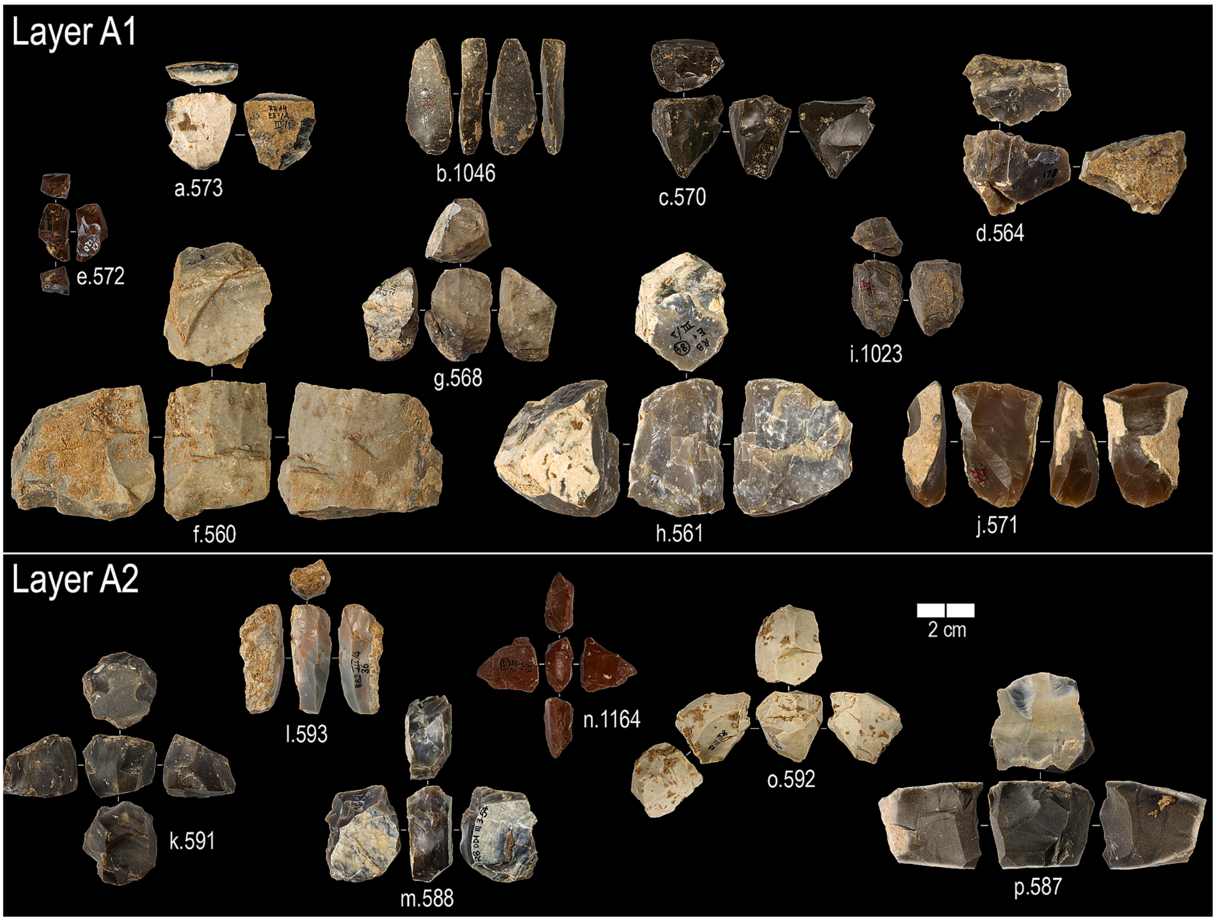

Fig. 5. Sample of laminar cores from layers A2 and A1. Cores are classified as follows: (a, i) wide-faced flat; (b) burin core; (c, j, o) multi-platform; (d) initial; (e, n) bipolar; (f, h, k, l, p) semi-circumferential; (g, m) narrow-sided. Cores are sorted according to raw material provenance as follows: (a, j) very distant French chert; (b, c, k, m, p) distant French chert; (d, f, g, h) local chert; (e, n) distant Italian radiolarite; (i, l) very distant Italian chert; (o) circum-local French chert. The numbers following the letters correspond to the lithics' IDs as reported in the associated dataset (Photos: A. Falcucci).

assemblages cannot fully explain the very low refit rate. An additional factor is likely the palimpsest nature of cave sites and rockshelters, where limited areas are reoccupied multiple times throughout the formation of the stratigraphic sequence (Bel et al., 2020). In terms of excavation extent, Falcucci et al. (2024b) found a large number of break connections between fragments located at short distances from each other, categorized as short refittings (<0.5 m), as defined by Cziesla (1990).

The integrity of the studied layers can be inferred from other evidence, such as the spatial analysis by Vallerand et al. (2024). The authors show that part of the excavation is located between the shelter wall and the boulders' dripline, which led to good preservation of the spatial organization of materials and activities at the site, with limited artifact dispersion. Interestingly, the two connections found are associated with areas of high artifact density, both in A2 and A1. In A2, which corresponds to a relatively structured occupation in terms of spatial organization, the connection was found near the hearth. In A1, the connection was found near the dripline's boulders, where comparatively more materials were recovered than in A2. These lines of evidence suggest that the low conjoining rate may have been partly influenced by the intensity and strategy of occupation during the formation of layers A2 and A1. In this regard, the frequency of lithic production at the site is an important factor to consider. For example, it has been suggested that retooling activities and the disposal of broken implements were significant aspects of the human activities in A1 (Riel-Salvatore & Negrino, 2018b).

Considering the two break connections identified, it is important to note that both are intra-layer, suggesting minimal vertical displacement of artifacts. When combined with the spatial data, this indicates good integrity of the lithic assemblages and the preservation of the spatial organization within the shelter. The observed differences in reduction intensity and raw material use would likely not be as pronounced if substantial post-depositional mixing of the sequence had occurred. Additionally, there is a marked variation in the spatial arrangement of the site between the two layers (Vallerand et al., 2024), as also confirmed by studies on animal resource exploitation (Pothier-Bouchard et al., 2020). Finally, Holt et al. (2019) found limited disturbance due to animal burrowing, suggesting minimal inter-stratigraphic movement of

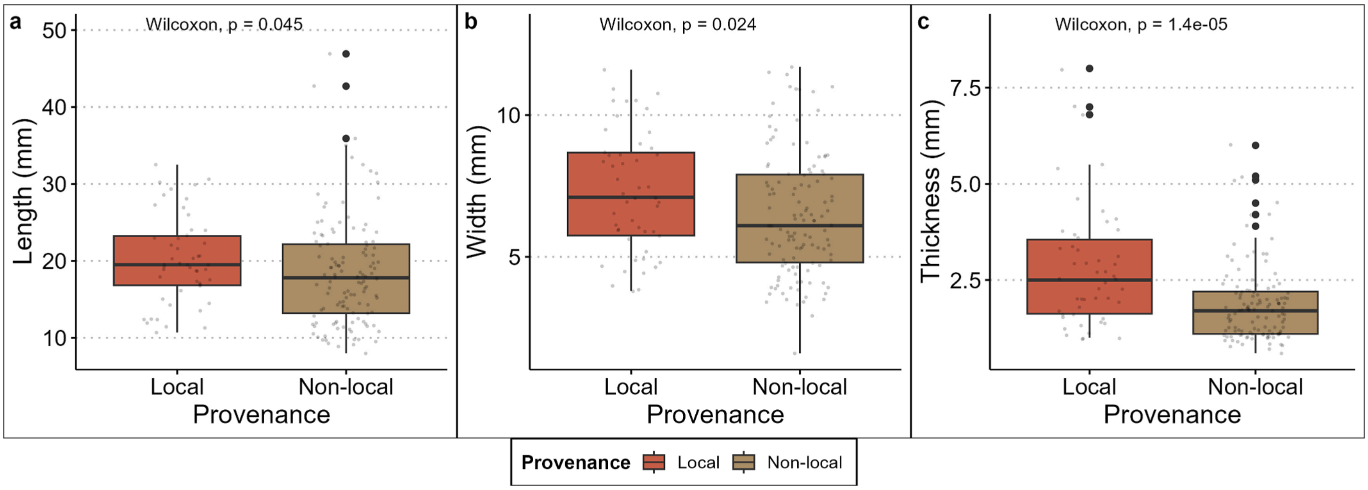

Fig. 6. Distribution of length, width, and thickness of complete bladelets from layer A1, sorted by local and non-local (i.e., circum-local, distant, and very distant) raw materials.

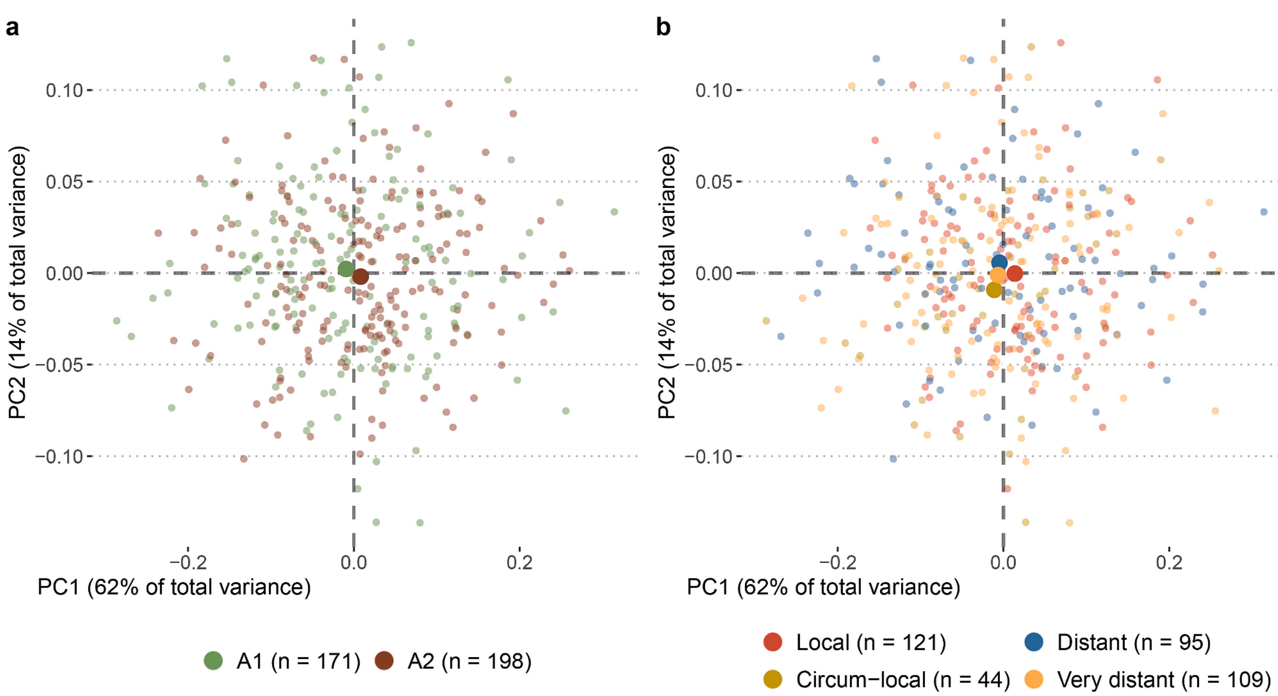

Fig. 7. Biplots of Principal Component (PC) axes 1 and 2 resulting from the 2D outline analysis of complete bladelets. (a) Bladelets sorted by layer; (b) bladelets sorted by raw material provenance. Mean values for each group are displayed as larger dots. Refer to the legends for group color-coding.

materials. This was also observed at the stratigraphic interface between layer A2 and the semi-sterile Mousterian layer below (Riel-Salvatore et al., 2022). On the other hand, it is important to mention that the radiocarbon dating performed at the site on charcoal and bone yielded inconsistent results (Benazzi et al., 2015), with several samples being too young for their stratigraphic position (Zilhão et al., 2024), necessitating further analyses that are beyond the scope of this paper.

Finally, this study does not provide evidence to discuss the integrity of spatial activities in the exterior area of the rockshelter, nor break connections linking this area with the shelter interior and the dripline. Pothier-Bouchard et al. (2024) proposed that the two hearths in layer A1 are not associated with a single occupational event, but rather represent distinct, possibly short-term, episodes of site visitation. Future studies should thus expand the break connection search to other tool types (e.g., retouched bladelets), as well as the search for lithic technological refits (Romagnoli & Vaquero, 2019) and bone refits (e.g., Modolo & Rosell, 2017; Morin et al., 2005).

5.2. *Testing differences in mobility strategies between layers A2 and A1*

The geomorphology of Liguria, situated at the interface between the Maritime Alps, the Apennines, and the Ligurian Sea, has created a preferential corridor for human movement along the Mediterranean since prehistoric times (Negrino et al., 2023). The Balzi Rossi complex, with its numerous prehistoric sites, has enabled archaeologists to extensively discuss human mobility, particularly through the circulation of high-quality raw material sources, extending from the Rhône Valley to the Umbrian-Marchean Apennine. In this context, the data collected over several fieldwork seasons positions Bombrini as a pivotal site for discussing the internal variability of the PA in Europe—a topic often set

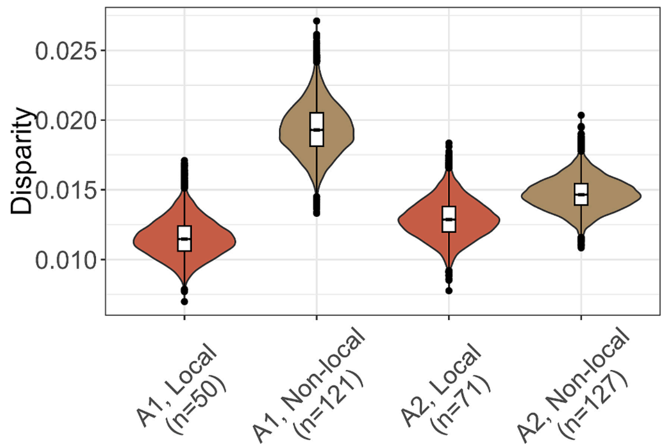

Fig. 8. Boxplots visualizing the sum of variance (disparity) for all complete bladelets from layers A2 and A1, sorted by local and non-local (i.e., circum-local, distant, very distant) raw materials.

aside in favor of addressing issues related to cultural taxonomy. This updated analysis, incorporating all lithic artifacts recovered up to the conclusion of the archaeological excavations, provides additional evidence to support and further elaborate on the mobility strategies at Bombrini, complementing the interpretations published thus far.

Previous research suggested that layer A1 formed as a result of short-term, frequent occupations primarily driven by residential mobility strategies, with a technological emphasis on curation. Our new data confirms a marked exploitation of local resources in A1, as evidenced by the high number of laminar cores and the totality of flake cores made from local chert. Blanks linked to the initialization of laminar cores are more often made from local raw materials, indicating that production with these materials occurred on-site. The slightly higher frequency of retouched bladelets made from distant cherts compared to A2 suggests more retooling in this layer, with multi-component tools maintained using local raw materials.

Interestingly, there is also a higher frequency of unretouched

Table 6
Classification of tool types from layers A2 and A1, with percentages provided in brackets.

	A1	A2	Total
Burin carinated	1 (0.5 %)	0 (0.0 %)	1 (0.2 %)
Burin multiple	1 (0.5 %)	0 (0.0 %)	1 (0.2 %)
Burin simple	3 (1.6 %)	7 (2.8 %)	10 (2.3 %)
Composite tool	5 (2.6 %)	2 (0.8 %)	7 (1.6 %)
Endscraper carinated	1 (0.5 %)	1 (0.4 %)	2 (0.5 %)
Endscraper simple	9 (4.8 %)	7 (2.8 %)	16 (3.6 %)
Endscraper thick-nosed	0 (0.0 %)	1 (0.4 %)	1 (0.2 %)
Rabot	1 (0.5 %)	0 (0.0 %)	1 (0.2 %)
Retouched blade	9 (4.8 %)	17 (6.7 %)	26 (5.9 %)
Retouched bladelet	144 (76.2 %)	197 (77.9 %)	341 (77.1 %)
Retouched flake	10 (5.3 %)	16 (6.3 %)	26 (5.9 %)
Scaled piece	2 (1.1 %)	5 (2.0 %)	7 (1.6 %)
Truncation	3 (1.6 %)	0 (0.0 %)	3 (0.7 %)
Total	**189**	**253**	**442**

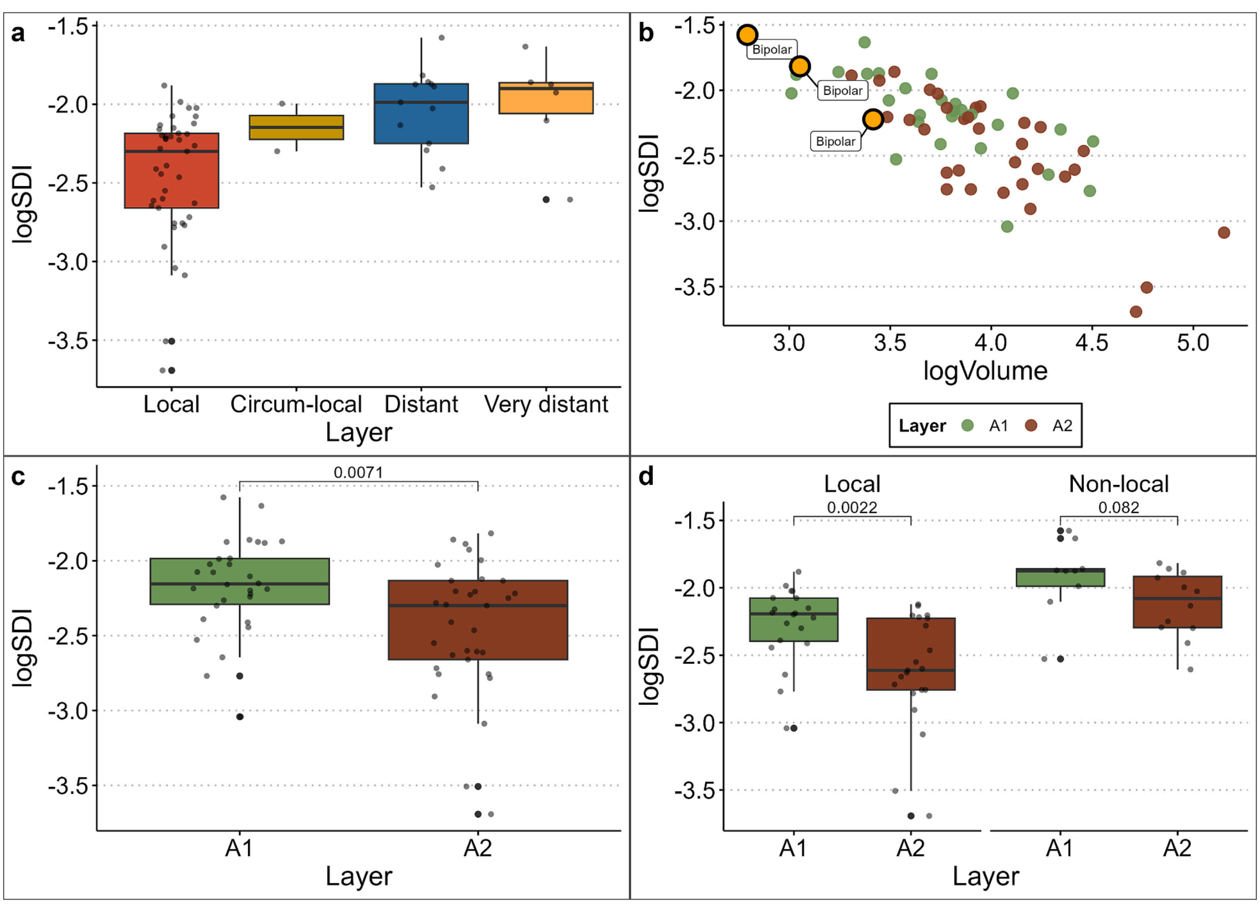

Fig. 9. Core reduction intensity analysis. (a) Boxplots showing the distribution of logarithmically transformed Scar Density Index (logSDI) values of cores sorted by raw material provenance; (b) logSDI plotted against the logarithmically transformed volume (logVolume) of cores from layers A2 and A1; (c) boxplots of logSDI values of cores classified by layer with a comparison of means; (d) boxplots of logSDI values of cores classified by layer and raw material provenance with an intra-layer comparison of means.

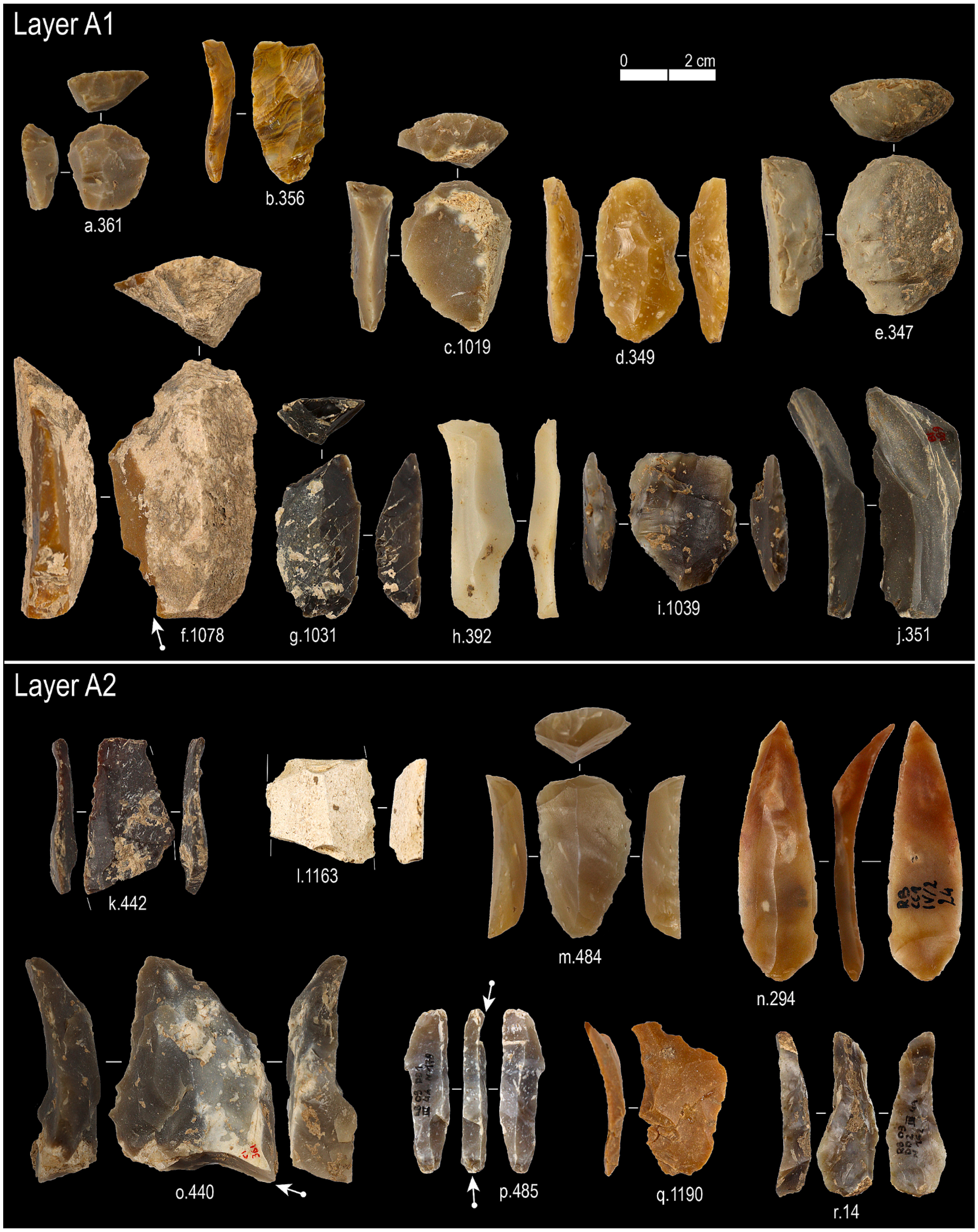

Fig. 10. Selection of tools from Layers A1 and A2. (a, c) Endscrapers on flake; (b, j, k, l, n, r) retouched blades; (d, i, q) retouched flakes; (e) endscraper on flake with lateral retouch; (f, o) endscrapers and burins on flake; (g) truncation on flake; (h) truncation on blade; (m) double endscraper on flake with lateral retouch; (p) burin on a bladelet spall. Tools are sorted by raw material provenance as follows: (a, f, l, p) circum-local French chert; (b, c, e, g, k, o, r) local chert; (d, j, q) very distant Italian chert; (h, i) distant French chert; (m, n) very distant French chert. The numbers following the letters correspond to the lithics' IDs as reported in the associated dataset (Photos: A. Falcucci).

bladelets made from distant and very distant sources in A1, suggesting three interrelated scenarios: (a) that cores from distant sources were brought to the site and finally exhausted, (b) that some of these bladelets were used in multi-component tools without being retouched, and (c) that unretouched bladelets were transported and introduced to the site. The first possibility is supported by the higher share of distant and very distant blanks other than bladelets (e.g., flakes and blades). Tools used for domestic activities are more frequently made from local materials, suggesting that these items were crafted for specific tasks at the site and were less often exported. The SDI data further indicate that laminar cores in A1 are more intensely reduced compared to those in A2, especially those made from local rocks. Similarly, cores from distant and very distant sources are generally more reduced than those made from local and circum-local sources.

The increased reduction intensity in A1 is also reflected in the reduced size of unretouched bladelets made from non-local materials compared to A2. Additionally, cores from non-local sources were imported at a more advanced stage of the reduction sequence in A1. The role of reduction intensity in the size of unretouched bladelets is also evident in the strong similarity in the shape of retouched bladelets between A2 and A1, independent of raw material type. This suggests a notable standardization in bladelet production during the PA (Kuhn,

Fig. 11. Selection of retouched bladelets from layers A2 and A1. Retouch positions are as follows: (a, b, c, d, e, f, g, i, j, l, m, n, o, p, q, r, u, v, x, y) inverse unilateral; (h, s) direct unilateral; (k, t, w) alternate. Bladelets are sorted by raw material provenance as follows: (a, k, w) very distant Italian chert; (b, m, q, x) very distant French chert; (c, l, y) circum-local French chert; (d, e, f, g, h, n, p, r, s) distant French chert; (i, j) undetermined; (o, u) local; (t, v) distant Italian radiolarite. The numbers following the letters correspond to the lithics' IDs as reported in the associated dataset (Photos: A. Falcucci).

Table 7
Retouch position recorded on bladelets from layers A2 and A1, with percentages in brackets.

	A1	A2	Total
Alternate	15 (10.4 %)	33 (16.8 %)	48 (14.1 %)
Crossed	2 (1.4 %)	1 (0.5 %)	3 (0.9 %)
Direct	18 (12.5 %)	14 (7.1 %)	32 (9.4 %)
Inverse	109 (75.7 %)	149 (75.6 %)	258 (75.7 %)
Total	**144**	**197**	**341**

2002). Interestingly, the disparity analysis reveals that unretouched bladelets from A1 exhibit more marked internal shape variance compared to those from A2, possibly indicating that these bladelets were produced from a higher number of cores, resulting in greater internal variability depending on their geometric features. However, this higher variance may also account for the presence of several bladelets made from exotic raw materials that were imported rather than produced on-site.

Overall, our new data supports the interpretation of A1 as a more curated system with shorter-term occupations and a residential strategy within the forager-collector continuum (Riel-Salvatore & Negrino, 2018b). For layer A2, instead, our results reinforce the interpretation of this deposit as associated with logistical mobility patterns and a more expedient lithic technology (Riel-Salvatore & Negrino, 2018b).

A2 is richer in archaeological content compared to A1, with a greater number of tools and cores, many of which are made from non-local raw materials. The presence of cores made from circum-local rocks, which are absent in A1, suggests that the camp was supplied with non-local resources through systematic forays to procurement sites. In this regard, laminar production on exogenous materials was often initiated on-site, in contrast to A1, as evidenced by the higher proportion of crested blanks made from these materials. This pattern contrasts with the rest of the blanks, which are more often made from locally available rocks. This may suggest that these high-quality raw materials were primarily used for the production of bladelets intended for hafting multi-component projectile weapons, with bladelets being exported from the site during hunting forays and discarded at task sites away from the camp, as already proposed by Riel-Salvatore & Negrino (2018b). Moreover, the similarities in the size of unretouched bladelets and the less pronounced differences in disparity scores between local and non-local rocks provide further evidence for the more intense on-site production of blanks using a variety of raw material sources.

Further confirmation of the logistical land-use strategy in A2 is provided by the SDI data, which show that several cores are less reduced, suggesting that non-exhausted cores were less frequently removed from the site, as instead seen in A1. This more expedient technological organization is also supported by the recovery of tested cores, which likely indicates the systematic stockpiling of raw materials (i.e., provisioning places: Kuhn, 1995), and the high presence of cores with exclusive flake removals, accounting for 58 % of the total cores recovered. Interestingly, several flake cores are made from exogenous rocks, which can be linked to the recycling of bladelet cores and a reduced interest in removing rarer raw materials from the site. This behavior is further confirmed by the discard of a higher number of domestic tools made from very distant raw materials. The differing behavioral strategies identified in A2 led Riel-Salvatore & Negrino (2018b) to describe the evidence of human occupations in A1 as a less wasteful strategy.

Our new assessment of lithic technology and raw material strategies

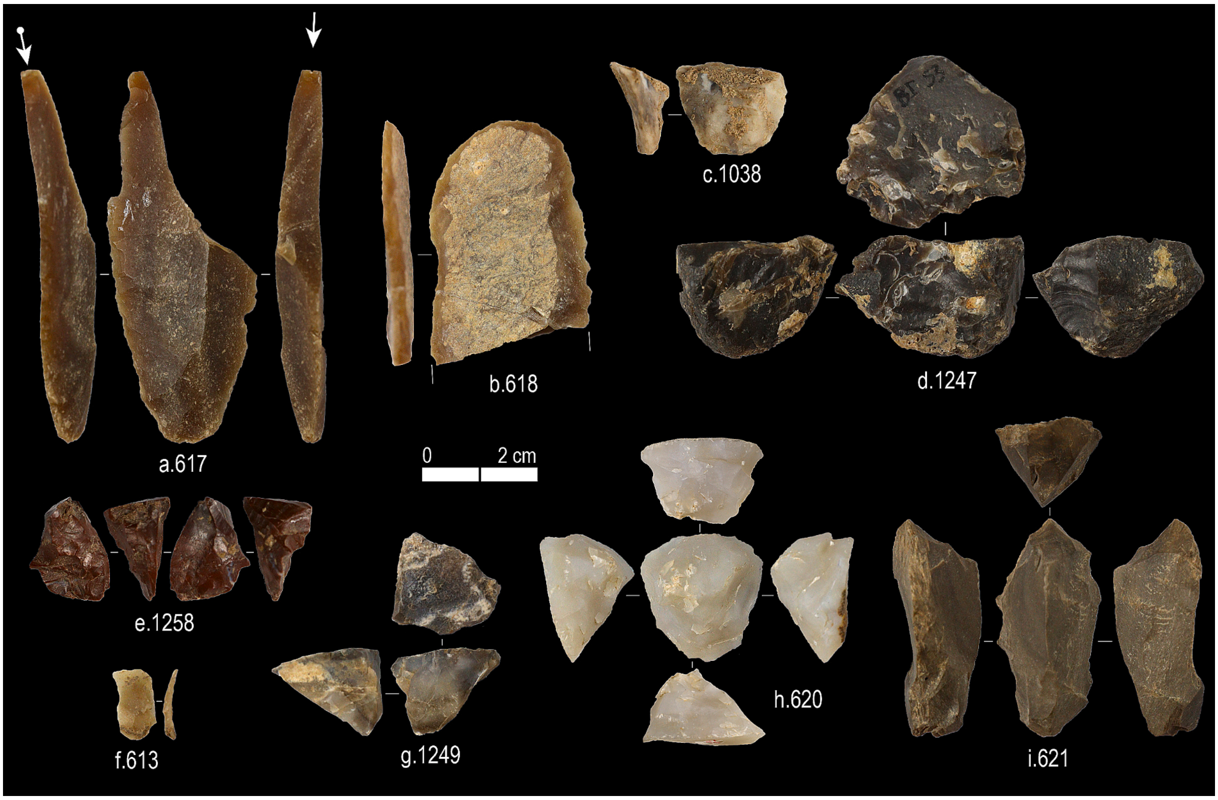

Fig. 12. Selection of tools, cores, and blanks from layer A0. (a) Retouched blade with burin spalls; (b) endscraper on a cortical blade with lateral retouch; (c) maintenance flake from bladelet production; (d) initial core; (e) bipolar core; (f) non-cortical bladelet; (g) laminar core shatter; (h) carinated endscraper; (i) thick-nosed endscraper. Lithics are sorted by raw material provenance as follows: (a, b, i) distant French chert; (c, d, g) local chert; (e) distant Italian radiolarite; (f) very distant French chert; (h) circum-local French chert. The numbers following the letters correspond to the lithics' IDs as reported in the associated dataset (Photos: A. Falcucci).

complements the interdisciplinary data published for Bombrini. The spatial analysis suggests that A2 is the densest and most spatially structured layer, with distinct functions between the exterior and interior of the rockshelter and evidence for prolonged and recurrent visits. Preliminary data on seasonal indices suggest that human occupations in layer A2 were prolonged, likely extending into harsher seasons. In contrast, layer A1 shows no evidence of seasonality, as indicated by the absence of seasonal indices (Pothier-Bouchard et al., 2020). In layer A2, there is evidence of repeated use of bones as fuel within the shelter interior, suggesting prolonged stays at the camp (Pothier-Bouchard et al., 2024). Furthermore, A2 shows more evidence of waste management and space clearing, whereas layer A1, despite the presence of two hearths and a pit, exhibits less rigid spatial organization (Vallerand et al., 2024). Overall, the combined data from Bombrini represents compelling evidence of internal variability within the PA, further confirming the resilience of PA foraging groups to changing environments (Riel-Salvatore & Negrino, 2018a).

5.3. Contextualizing the technological systems of layers A2 and A1

Due to its high-resolution data and the wealth of information gathered in recent years, Bombrini offers a unique opportunity to discuss technological and behavioral variability in the context of the early Upper Paleolithic in Mediterranean Europe. Both layers A2 and A1 are characterized by a technological system largely comparable to most PA assemblages (e.g., Bon & Bodu, 2002; Bon, 2002; Chu et al., 2022; Falcucci et al., 2017; Falcucci et al., 2024a; Normand, 2006; Tafelmaier, 2017; Teyssandier, 2023). This system is defined by the use of direct marginal percussion to produce slender bladelets from unidirectional platform cores with plain striking platforms. The need to produce standardized bladelets, as evidenced by the similarity in shape and size of bladelets made from different raw materials, suggests a technology aimed at producing multi-component tools (Pasquini, 2013). This is further supported by the frequent marginal retouching of bladelets (Falcucci et al., 2018), which is well-represented in both PA assemblages at Bombrini. The use of the same initialization and maintenance operations on both the cores' striking platforms and flaking surfaces further demonstrates how these assemblages share a common technological system.

The technological investment in the production of other blanks, such as flakes and especially blades, is less pronounced in the PA compared to later stages of the Aurignacian (Bon et al., 2010). In the PA, these blanks are mostly used to produce tools such as endscrapers for activities like hide-working (Aleo et al., 2021). The reliance on low-quality raw materials for flake production at Bombrini, as well as at the nearby site of Mochi (Grimaldi et al., 2014; Kuhn & Stiner, 1998), further supports the idea of distinct approaches to core reduction depending on the production goals.

Our data indicate that foragers visiting Bombrini during the formation of layers A2 and A1 were familiar with a vast region stretching from the Rhône Valley to the Central Apennines. Raw material provenance serves as the most surprising evidence of this cross-regional connectedness, suggesting not only more complex mobility strategies compared to the previous Mousterian but also inter-regional contacts between foraging groups navigating this vast region (Fig. 13). These networks likely facilitated the transfer of technological knowledge, contributing to the high similarity between PA assemblages across Mediterranean Europe (Falcucci et al., 2024a). Inter-regional contacts appear to have been particularly important between Liguria and Provence, likely facilitated by the geomorphology of the Liguro-Provençal Arc, as also as

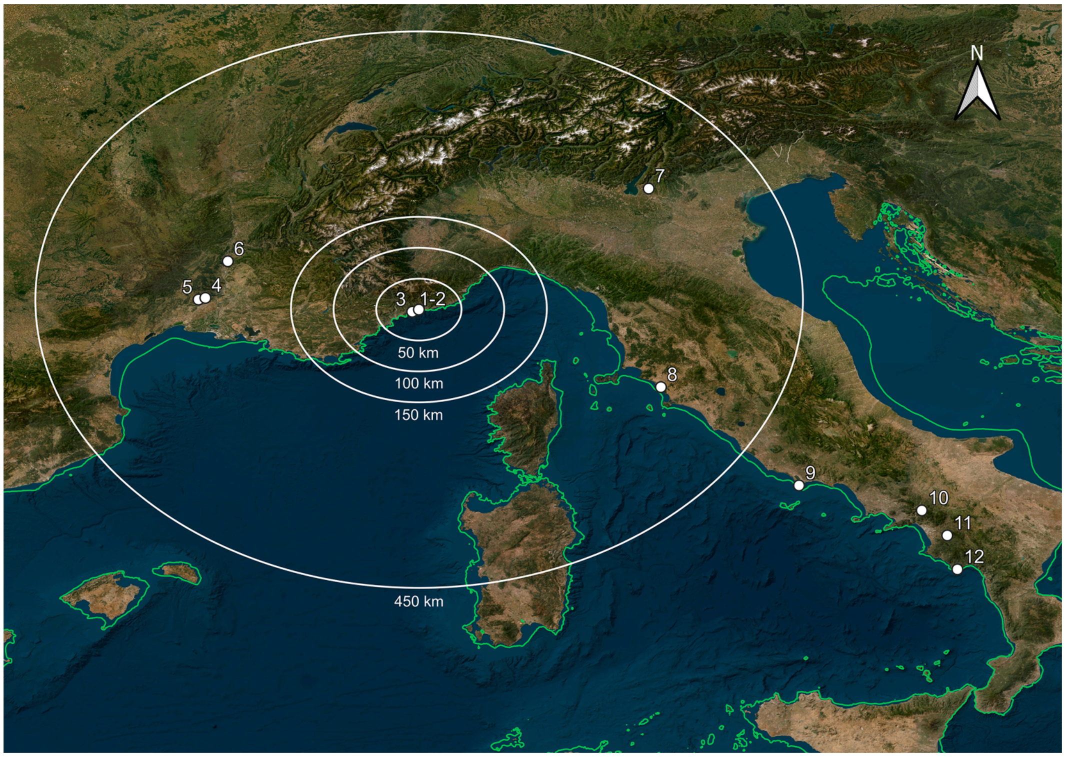

Fig. 13. Map of Italy and the Liguro-Provençal Arc showing the geographic locations of the Protoaurignacian and Early Aurignacian sites cited in the paper, along with schematic identification (ellipses) indicating the distances of lithic raw material sources from Riparo Bombrini, categorized as presented in the paper. The largest ellipse (i.e., 450 km) represents the estimated distance from where the Scaglia Rossa and Scaglia Variegata (Umbrian-Marchean Apennine) were sourced. Sites: (1–2) Riparo Bombrini and Riparo Mochi; (3) Grotte de l'Observatoire; (4) La Laouza; (5) Esquicho-Grapaou; (6) Grotte Mandrin; (7) Grotta di Fumane; (8) La Fabbrica; (9) Grotta del Fossellone; (10) Serino; (11) Grotta di Castelcivita; (12) Grotta della Cala. The map includes a green line representing the reconstructed mean sea level at −65 m above the current sea level, using the Paleocoastlines GIS dataset (https://crc806db.uni-koeln.de/dataset/show/paleocoastlines-gis-dataset1462293239/). The map was generated in QGIS v. 3.28. (Map: M. Del Rio). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the case in other periods of the Upper Paleolithic (Negrino & Starnini, 2003; Peresani et al., 2018; Tomasso & Porraz, 2016; Tomasso et al., 2016).

The nearby site of Mochi provides additional insight into foraging mobility and technological behavior during the PA. The most important PA assemblage at Mochi comes from stratigraphic unit G (Kuhn & Stiner, 1998), which contains a lithic assemblage largely comparable to Bombrini, with a chronology dating as early as 43–42 ky cal BP (Douka et al., 2012; Frouin et al., 2022). However, stratigraphic unit G is not the oldest at the site according to Grimaldi et al. (2014). The authors described a very small PA assemblage in the intermediate stratigraphic unit G–H, which shares technological and typological similarities with the base of stratigraphic unit G. The main difference between G–H and G is the increased use of local raw materials in the former stratigraphic unit, as well as the absence of Dufour bladelets. On the other hand, exogenous raw materials were still sourced from distant regions. Grimaldi et al. (2014) hypothesized that this variation may be linked to the rapid expansion of the PA or a shift in the role of Mochi within the territory used by these foraging groups. It should, however, be mentioned that the very limited sample size of the G–H assemblage (n = 221) warrants caution against overinterpretation of these findings. Additionally, no consideration is given to the likelihood of exchange of high-quality raw materials between groups settled in adjacent regions.

The variability in the use of exogenous raw materials is evident when comparing Mochi to the nearby site of Observatoire, where 85 % of the discarded materials (e.g., cores and retouched bladelets) are sourced from western Provence, over 130 km away as the crow flies. Due to the limited lithic sample, Porraz et al. (2010) hypothesized that the formation of the PA assemblage at Observatoire resulted from infrequent visits by small groups who directly collected raw materials in western and eastern Provence and transported them between sites within a residential mobility system, similar to the case of layer A1 at Bombrini. According to Porraz et al. (2010), the high proportion of raw materials from western Provence suggests that this region was the main area inhabited by PA foraging groups.

In the Rhône Valley, particularly to the west of the Rhône river, there appears to be a decrease in the use of exogenous materials, likely due to the higher quality of local raw materials, which required less effort in procurement. It should be mentioned that the differential use of exogenous raw materials is a common feature of the PA. For instance, at sites like Arbreda, raw materials were sourced at least 100 km as the crow flies from the site due to the scarcity and poor quality of local outcrops (Ortega Cobos et al., 2005) . At Mandrin in the Middle Rhône Valley, on the other hand, the only non-local material coming from the small PA assemblage was sourced about 80 km away as the crow flies (Slimak et al., 2006b; Slimak et al., 2006a). Further south and west of the Rhône River, important PA sites include La Laouza and Esquicho Grapaou (Bazile, 1974, 2005). Recent dating of the PA at Esquicho Grapaou places it between 42 and 40 ky cal BP (Barshay-Szmidt et al., 2020). Layer SLC1a + b at Esquicho Grapaou and Level 2b1 at La Laouza are similar in technology to Bombrini, with several platform cores and retouched bladelets, most often modified on the ventral face (Sicard, 1994, 1995). At both sites, raw materials were in most cases local, sourced from within 8–10 km as the crow flies of the site (Bazile, 2005). However, a notable finding in the PA of Esquicho Grapaou is the identification of an unretouched blade fragment and two unretouched bladelet fragments made from Scaglia Rossa, sourced from the Umbrian-Marchean Apennine, representing the most distant evidence for the transport of this raw material type during the Aurignacian (Bertola & Broglio, 2021).

Along the Tyrrhenian coast of Italy, the PA is known at the sites of Grotta della Fabbrica (Dini et al., 2012), Grotta di Castelcivita (Falcucci et al., 2024a; Gambassini, 1997), and Serino (Accorsi et al., 1979). Castelcivita and Serino are particularly noteworthy due to its very southern geographical location. As at Bombrini, bladelets were primarily modified by inverse retouching and were often detached from volumetric platform cores at both sites. At La Fabbrica, Dini et al. (2012) identified about 6 % of allochthonous raw materials, particularly Scaglia Rossa from the Marche region, approximately 160 km as the crow flies from the site. No raw material studies have been conducted at Castelcivita, but most lithics appear to have been made from locally available materials, primarily cherts and radiolarites (Riel-Salvatore & Negrino, 2009). Falcucci et al. (2024a) noted an increase in carinated cores at Castelcivita, which contrasts with the PA to the north. Since the PA layer at Castelcivita starts later than the PA sites to the north (Higham et al., 2024), this difference may be related to internal variability within the PA, rather than being solely due to the volumetric features of the collected raw materials (Falcucci et al., 2024a).

In northeastern Italy, Fumane, dating roughly contemporaneously with the PA sites in Liguria, is particularly important due to the discovery of a HS tooth in the lowermost PA stratigraphic unit, A2. At Fumane, Falcucci et al. (2018) noted a more variable retouched bladelet assemblage compared to the sites along Tyrrhenian Italy, with an increased number of direct and alternate modifications. Additionally, reduction procedures at Fumane targeted more often pointed bladelets by isolating convergent flaking surfaces (Falcucci & Peresani, 2018), a feature less common at Bombrini and Castelcivita (Falcucci et al., 2024a). Despite these differences, a significant finding at Bombrini—a sidescraper made from a flake of pre-Alpine chert from layer A1 (Fig. 10d), commonly found in the western Lessini Mountains where Fumane is located—suggests some exchanges between these regions. These exchanges appear to have been sporadic compared to the overwhelming presence of chert from regions situated before the Maritime Alps and the Ligurian Apennines, suggesting that the Po Plain may have acted as a geographical barrier during the Aurignacian (Bertola et al., 2018; Negrino & Riel-Salvatore, 2018).

5.4. Discussing the lithic assemblage from layer A0

Despite the small size of the assemblage, which warrants caution against over-interpretation, the techno-typological features of layer A0, along with its stratigraphic position above layer A1, suggest an attribution to the Early Aurignacian (Bon et al., 2010). This attribution is supported by data from nearby sites such as Mochi (Tejero & Grimaldi, 2015) and Observatoire (Porraz et al., 2010), where Early Aurignacian assemblages have been described. The recovery of two carinated cores, typologically classified as a carinated endscraper and a thick-nosed endscraper, is particularly noteworthy, as is the close similarity between the complete bladelets and the flaking surface lengths of these pieces. This contrasts markedly with the longer bladelets found in layers A2 and A1. Additionally, two of the three retouched bladelets exhibit direct modification, aligning with the increased frequency of bladelets with direct retouching observed at the top of stratigraphic unit G and the bottom of stratigraphic unit F at Mochi (Laplace, 1977), layer gic at Castelcivita (Falcucci et al., 2024a), and stratigraphic unit D3b alpha at Fumane (Falcucci et al., 2024b). In layer A0, the retouched blades are also wider and thicker, highlighting a clear dissociation between the production of miniaturized bladelets and larger blades, as frequently noted in the Early Aurignacian (Bon, 2002; Teyssandier, 2007).

In Italy, the Early Aurignacian is recognized outside Liguria, at sites such as Fumane (stratigraphic unit D3b alpha; Falcucci et al., 2024b), Grotta del Fossellone (layer 21; Blanc & Segre, 1953; Degano et al., 2019), and in the southern regions of the Peninsula at Castelcivita (layers gic and ars; Falcucci et al., 2024a), and Grotta della Cala (sub-layers AU10-AU10; Falcucci et al., 2025c). These recent findings align with data from other western European sites (Bordes, 2002; Normand, 2006; Roussel & Soressi, 2013; Santamaría, 2012, among several others), confirming that the Early Aurignacian developed as early as 40 ky cal BP, slightly prior to the Campanian Ignimbrite super-eruption, and persisted through Heinrich Event 4 and into the onset of GI8 (Banks et al., 2013; Frouin et al., 2022; Higham et al., 2024; Teyssandier, 2023; Wood et al., 2014). Overall, the circulation of raw materials from the Rhône Valley to the Central Apennines, as observed in layer A0 at Bombrini, along with the presence of Early Aurignacian assemblages at sites such as Mochi, Observatoire, and Esquicho-Grapaou (Bazile, 1974, 2005), suggests a uniform cultural development across Mediterranean Europe, albeit the expected regional variations and internal variability resulting from different mobility patterns and subsistence systems (Discamps et al., 2011).

5.5. Towards an integrated anthropological perspective on the Protoaurignacian

Over the past decades, the re-evaluation of material from classic sites complemented by the excavation of new archaeological deposits have refined our understanding of the nature of the PA in the broader context of the Aurignacian cultural phenomenon (Bar-Yosef & Zilhão, 2006). The present study contributes to the growing appreciation of the fact that PA assemblages often reveal a substantial amount of internal variability that opens up anthropological inquiry into human behavior over the duration of this phase, eschewing prime movers and one-size-fits-all explanations. By characterizing some of this variability in terms of how it relates to large-scale trends in mobility strategies, it opens up its analysis in the context of broader anthropological debates and discussions about forager lifeways stretching back into the Paleolithic. For instance, confirming that the assemblage from layer A2 at Bombrini was accumulated under an overall more logistical land-use regimen to occupy the site and exploit its surrounding can tie into work about the notion of risk-management by foragers just prior of HE4 (Winterhalder, 1986). Recent work (e.g., Grove, 2010) has for instance proposed that in certain contexts foragers adopted logistical mobility strategies as a way to buffer against risk in subsistence patterns. This can serve as a framework to understand some of the choices made by the PA occupants of layer A2 in contrast to those from layer A1, where subsistence risk may have been perceived differently under distinct ecological and social conditions. Likewise, this provides an interesting context to recently published evidence of plant grinding and flour production from wild cereals in the PA layers at Bombrini (Mariotti Lippi et al., 2023).

In a like manner, the data presented in this study also help recenter debates on potential diffusion routes of the PA into the Italian Peninsula, but also to reframe some of the ways in which the earliest phases of this technocomplex have been interpreted. Specifically, it moves the debate beyond simply establishing whether variability within the PA reflects 'pioneering' or exploratory expressions in its early stages, as opposed to more established or fully expressed versions in later phases (Davies, 2001, 2007; Rockman, 2003). Indeed, by showing that the internal variability of the PA was the result of choices and strategies made against broader patterns of ecological variability (e.g., Paquin et al., 2024), it highlights that these decisions were not solely determined by chronology or habitat variables. This being the case, it now situates the PA as a prime candidate to explore, in future studies, dimensions of mobility that go beyond simple adaptive poses (Kuhn, 2020) and tackle it as a possible reflection of active investment in the crafting of social networks predicated on other considerations than resource acquisition. In this context, and using risk management as an overall conceptual anchor, exploring the role of information and network building at macroregional scales (Whallon, 2006, 2011) emerges as a particularly promising avenue for future research, especially in light of an integrated perspective combining the lithic raw material procurement data presented in this study and information about social geography drawn from complementary data sources, such as ornamental shells possibly originating from the Atlantic façade of Europe (Gazzo et al., 2025).

6. Concluding remarks

Riparo Bombrini offers one of the richest archives for understanding the broad distribution of the PA across Europe, providing a crucial contrast to more geographically localized and partially contemporaneous technocomplexes such as the Uluzzian and Châtelperronian (Djakovic et al., 2022; Higham et al., 2024). First identified through Laplace's pioneering research at the Balzi Rossi sites (Laplace, 1966, 1977; Plutniak & Tarantini, 2016), the PA's considerable chronological span—lasting at least 2,500 years—underscores its adaptive resilience in response to shifting environmental conditions across Europe (Falcucci et al., 2024a; Riel-Salvatore & Negrino, 2018a). Within this context, Bombrini provides a unique opportunity to explore internal behavioral dynamics, despite notable techno-typological continuity between layers A2 and A1.

A particularly remarkable feature of the PA at Bombrini is the extensive circulation of lithic raw materials across the Liguro-Provençal Arc, suggesting sustained and robust information flow and interaction among highly mobile foraging groups from western Provence to the Ligurian-Tyrrhenian regions. This process likely facilitated the spread of technological knowledge, contributing to the striking material culture similarities observed across these areas. The diachronic persistence of these social networks is further supported by the newly documented techno-cultural shift to the Early Aurignacian in layer A0, aligning Bombrini's sequence with broader technological developments across western Europe (Teyssandier, 2023).

While similarities in lithic assemblages suggest social cohesion and technological exchange among foraging groups, the available data no longer support one-dimensional east-to-west diffusion models commonly invoked in discussions of HS dispersals (Anderson et al., 2015; Davies, 2001; Hublin, 2015). This challenges the prevailing narrative that the Early Ahmarian in the Levant was ancestral to the PA (e.g., Bosch et al., 2015; Slimak, 2023; Zilhão et al., 2024) and that its spread followed a straightforward westward trajectory (see also Kadowaki et al., 2015). Evidence of raw material circulation and use suggests that PA foragers were far from isolated pioneers entering unknown territories. Instead, the consistent west-to-east movement of lithic raw materials along the Liguro-Provençal Arc—also evident at the nearby site of Mochi (Frouin et al., 2022; Grimaldi et al., 2014; Kuhn & Stiner, 1998)—demonstrates a sophisticated understanding of their landscapes (Negrino et al., 2023).

Rather than representing movements driven solely by resource exploration, PA assemblages reflect deliberate strategic choices shaped by broader ecological and possibly social factors. Future research should further investigate the internal variability of the PA through an integrated anthropological lens, advancing our understanding of the PA not merely as a techno-economic adaptation, but as a socially embedded phenomenon within the broader dynamics of the European Upper Paleolithic.

CRediT authorship contribution statement

Armando Falcucci: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Funding acquisition. **Stefano Bertola:** Methodology, Investigation, Writing - Review & Editing. **Martina Parise:** Investigation, Data Curation. **Matteo Del Rio:** Visualization. **Julien Riel-Salvatore:** Investigation, Writing - Original Draft, Writing - Review & Editing, Funding acquisition. **Fabio Negrino:** Investigation, Resources, Writing - Review & Editing, Visualization, Funding acquisition.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jaa.2025.101705.

Data availability

The datasets generated and analyzed in the current study are available in the associated research compendium on Zenodo (Falcucci et al., 2025b): https://doi.org/10.5281/zenodo.15363594. The repository includes the lithic dataset, the R scripts to reproduce all results and figures of the study, as well as the 2D outline coordinates used in the geometric morphometrics analysis. Additionally, a dataset of 3D meshes of lithic artifacts (n = 110) from layers A2, A1, and A0 is available in a individual Zenodo repository (Falcucci et al., 2025a): https://doi.org/10.5281/zenodo.14731694.

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