frontiers | Research Topics

Human behavior, cognition, and environmental interactions for the lower paleolithic

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Published in
Frontiers in Earth Science
Frontiers in Ecology and Evolution

ISSN 1664-8714
ISBN 978-2-8325-2597-5
DOI 10.3389/978-2-8325-2597-5

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Human behavior, cognition, and environmental interactions for the lower paleolithic

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Citation
Moncel, M.-H., De Vos, J., Arzarello, M., eds. (2023). *Human behavior, cognition, and environmental interactions for the lower paleolithic*. Lausanne: Frontiers Media SA. doi: 10.3389/978-2-8325-2597-5

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TYPE Editorial
PUBLISHED 17 May 2023
DOI 10.3389/feart.2023.1205756

OPEN ACCESS

EDITED AND REVIEWED BY
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RECEIVED 14 April 2023
ACCEPTED 11 May 2023
PUBLISHED 17 May 2023

CITATION
Arzarello M, Moncel M-H and De Vos J (2023), Editorial: Human behavior, cognition, and environmental interactions for the lower paleolithic. *Front. Earth Sci.* 11:1205756. doi: 10.3389/feart.2023.1205756

Editorial: Human behavior, cognition, and environmental interactions for the lower paleolithic

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KEYWORDS

lower paleolithic, hominin activity, climate, environmental change, landscape interaction, raw material

Editorial on the Research Topic
Human behavior, cognition, and environmental interactions for the lower paleolithic

The Lower Paleolithic is commonly considered as a long period ca. 3.3 to 0.3 Ma, from the earliest evidence of lithic production to the apparition of new core technologies, such as the Levallois. Several Hominins (i.e., *Australopithecus, Homo habilis, Homo rudolfensis, Homo ergaster, Homo erectus, Homo heidelbergensis, Homo antecessor*. . .) as well as different "cultural traditions" (for instance Oldowan and Acheulean) have coexisted or have succeeded one another. Also considering the geographical extension (Africa, Asia, and Europe), we observe different Lower Palaeolithic cultural expressions under distinct environmental contexts and chronologies. Due to their latitudinal and longitudinal distribution, these traditions cover various climatic phases including roughly long and intense cold and cool periods.

This Research Topic, born under the impulse of the session "Lower Palaeolithic across time and space: what are we talking exactly about?" organized as part of the 19th UISPP worldwide congress, aims to investigate the variability of the Lower Palaeolithic cultural traditions across spatial and temporal scales, raising questions about the possible interaction between humans and climatic/environmental conditions:

- What exactly is the Lower Paleolithic and what environmental interactions could explain the variability of hominin adaptation? Were there common trends through the whole Lower Paleolithic independent of the environmental contexts?
- How hominins adapted to northern and cold conditions? What factors drove hominins to move North?
- How the raw material availability and the geological background influenced the Lower Palaeolithic traditions variability?
- Can we identify, during the Lower Palaeolithic, phenomena of convergence in hominin behavior and/or cognition flexibility to various geographical areas?

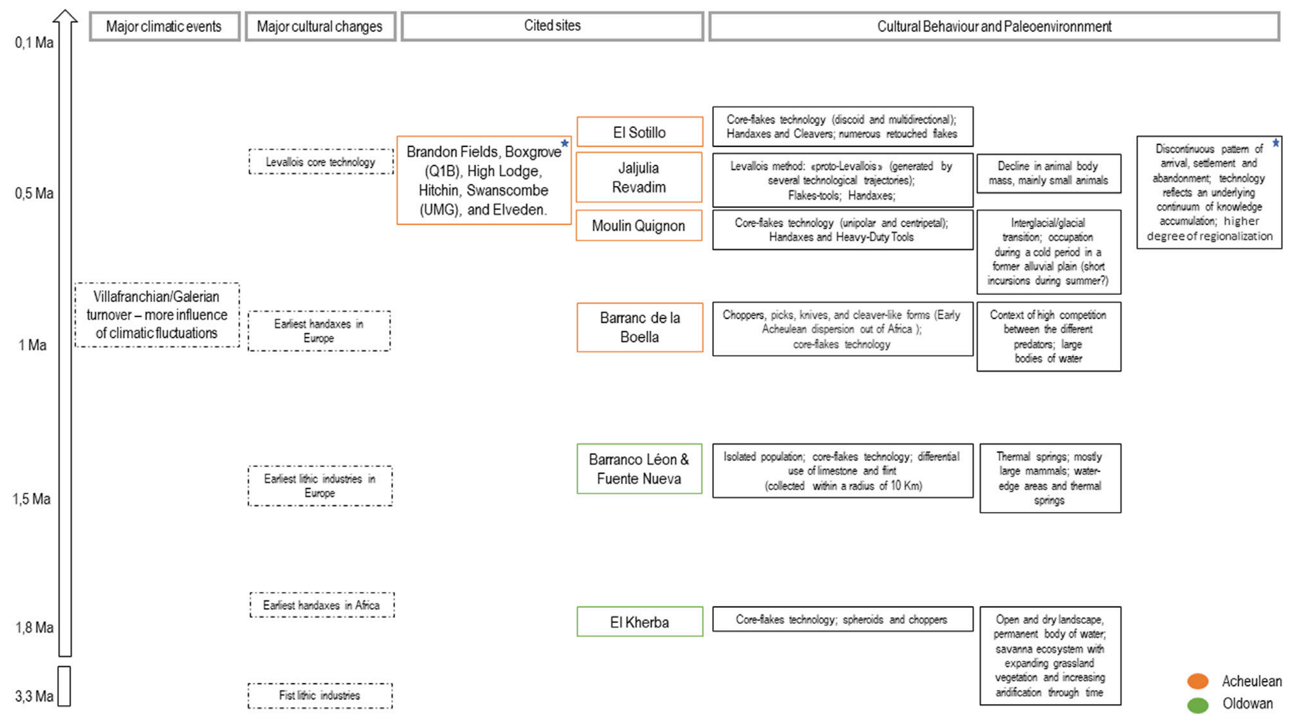

FIGURE 1
Main environmental and cultural characteristics of the prehistoric sites covered in the research topic. From a macroscopic point of view, it can be emphasised that the Villafranchian/Galerian turnover also corresponds to the spread of the Acheulean in Europe. It seems, however, that the environmental characteristics of the single sites have no obvious relationship with the technological production.

□ Can we define the *Homo* migration events in relation to the diffusion of Lower Palaeolithic cultures? How much did the climate influence "cultural regionalisms" and the spread of Oldowan and Acheulean traditions?

Increasing high-resolution paleoclimate proxies in many sites allow us to discuss the relationships between the environmental and archeological data, and the meaning of the lithic and faunal assemblages through technological and subsistence strategies.

Multidisciplinary research is necessary to deeply understand patterns of hominin behaviors during the Lower Paleolithic and adaptation to a significant variety of climatic/environmental contexts over time for this long period of time. Not being able to get a precise chronological framework (all radiometric dating, when available, has thousands of years of error), it is very complex to define a precise relationship between migration/diffusion, behavior, and climate on a global scale. For this reason, the only way to answer the questions listed above is to draw data from precise contexts that are as chronologically and geographically differentiated as possible. This Research Topic proposes to assemble papers that relate hominin behavior and detailed environmental data by the available multiple proxies. Papers focus both on continental and local cases to describe the different types of adaptations to environmental conditions and test them over time. Methodological developments are also a way to focus on case-studies in order to discuss the quality of records and the best methods to highlight the influence of climate on the hominin responses and strategies, and the resilience of populations through innovations, dispersals, and networks of sites. These approaches bridge the gap between archeological data and the Earth sciences.

The nine papers of this issue cover a large geographical area, from Western Europe, the Levant to North Africa with examples of open air sites in their environmental conditions (Figure 1). They also cover a large chronological period and offer the opportunity to compare evidence of the earliest occupations in North Africa (Abdessadok et al. dated to 1.8 Ma) and the Barsky et al. dated to 1.4–1.2 Ma. Evidence of the earliest evidence of Acheulean sites are focused on Western Europe, raising question on the environmental constraints related to the arrival of this new techno-complex in Europe (Olle et al., 0. 99 Ma, Spain; Garcia-Medrano et al. of the MIS 15-11; Moncel et al., 670 k, France; Santonja et al. basin of the second half of the Middle Pleistocene, Spain). The Levantine late Acheulian sites are reviewed through the sites of Rosenberg-Yefet et al. and Agam et al. where levels are dated to 500 ka.

Data indicate a large diversity in the technological strategies and the lithic assemblages for the earliest sites and a standardization (to the extent that this can be effectively recognized based on lithic assemblages) appears in late periods, such as the Late Acheulean Levantine sites or the British MIS 11 sites. That raises a question on hypotheses of first sporadic appearances of hominin in some areas and then massive spreads, with preliminary attempts at colonization or recurrent processes. Recently, methods used to study lithic industries have differed greatly, and questions to be able to compare results between sites, both for technology and for population movements in the environment (raw material supply areas). Compared to the past, a big step forward has been made in the approach to lithic assemblages, which are now analyzed from a global perspective that does not give different importance to the categories (e.g., shaping elements, tool kits, *etc.*). The concept of the "guide fossil" is certainly outdated in the context of a technological approach, and the characterization of lithic assemblages makes it possible to better highlight the peculiarities, but also the standardizations.

By the paleoenvironmental point of view, it seems that the Acheulean technology could have favored the dispersion of Hominins towards more northerly latitudes, reducing, at least in part, the impact of climatic conditions on the choice of territories to settle, punctually or continuously.

Particularly significant is also the discussion on the chronological limits of the Lower Palaeolithic (including Acheulean), which are defined on a cultural basis. This tradition is used with a global geographical meaning and is not defined on the basis of diffusion phenomena or major climatic changes. The articles presented in this Thematic Research Topic illustrate well how the upper limit of the Lower Palaeolithic is actually defined on the basis of a technical behavior whose actual importance/innovation is difficult to define. Can we still use the Levallois as a marker for the beginning of the Middle Palaeolithic?

Author contributions

MA, M-HM, and JV participated in the conception and drafting of the editorial.

Conflict of interest

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frontiers in Earth Science

ORIGINAL RESEARCH
published: 24 March 2022
doi: 10.3389/feart.2022.847358

Lower Paleolithic Winds of Change: Prepared Core Technologies and the Onset of the Levallois Method in the Levantine Late Acheulian

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OPEN ACCESS

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Specialty section:
*This article was submitted to
Quaternary Science, Geomorphology
and Paleoenvironment,
a section of the journal
Frontiers in Earth Science*

Received: *02 January 2022*
Accepted: *07 February 2022*
Published: *24 March 2022*

Citation:
*Rosenberg-Yefet T, Shemer M and
Barkai R (2022) Lower Paleolithic
Winds of Change: Prepared Core
Technologies and the Onset of the
Levallois Method in the Levantine
Late Acheulian.
Front. Earth Sci. 10:847358.
doi: 10.3389/feart.2022.847358*

The life cycle of a successful technological innovation usually follows a well-known path: a slow inception, gradual assimilation of the technology, an increase in its frequency up to a certain peak, and then a decline. These different phases are characterized not only by varying frequency of use but also by degree of standardization and distinguishability. The Levallois method, a sophisticated Middle Paleolithic technology aimed at producing desired stone items of predetermined morphology, is one such innovation. It has been repeatedly suggested that the Levallois method originated within earlier Lower Paleolithic Acheulian industries, and this work contributes to this discussion. We analyze the reduction trajectory of prepared cores and predetermined blanks from the late Acheulian sites of Jaljulia and Revadim, adding important new evidence for the Lower Paleolithic origins of the Levallois method and its adoption and assimilation in the human stone-tool repertoire of this period in the Levant. Revadim and Jaljulia also provide a rare opportunity to study patterns in the early assimilation of technological innovations. These sites yielded rich lithic assemblages typical of the late Acheulian in the Levant. The assemblages include handaxes but are mostly dominated by flake production technologies and flake-tools. The early appearance of prepared cores at both sites signals, in our view, the inception of concepts related to the Levallois method, termed here proto-Levallois, in the late Acheulian Levant. Through a detailed analysis of prepared cores and their products, we are able to characterize the early stages of assimilation of this method, using it as a case study in a broader discussion of the adoption and assimilation of technological innovations during Lower Paleolithic times.

Keywords: Levallois, prepared cores, Late Acheulian, technological innovation, core technology

1 INTRODUCTION

LEVALLOIS. Sometime a term becomes embedded with so much meaning that a single word can stand alone to serve as a code for a set of behaviors and capabilities that characterize early hominin adaptation. It is no wonder, then, that the origins of the Levallois method remain a central and controversial topic in Paleolithic archaeology.

The invention, introduction and assimilation of the Levallois method reflect a significant change in the cognitive and technological capabilities of Middle Pleistocene hominins (e.g., Bordes, 1971;

Ambrose, 2001; Wynn and Coolidge, 2010; Stout, 2011; Eren and Lycett, 2012; Cole, 2015; Stout, et al., 2015; Wynn and Coolidge, 2016; Muller et al., 2017). This method played a significant role in human adaptation over a vast time span of at least 200,000 years, before being replaced by blade production technologies at the advent of the Upper Paleolithic period, some 45/47,000 years ago (e.g., Boaretto et al., 2021).

Following central paradigms in Paleolithic research, it is generally accepted that Early-Middle Pleistocene technological concepts of stone-tool production and use are roughly correlated with the two major cultural complexes known as the Lower Paleolithic Acheulian and the Middle Paleolithic Mousterian (sometimes referred to as Mode 2 and Mode 3 technologies, e.g., Clark, 1969; Ambrose, 2001; Stout, 2010). The Lower Paleolithic Acheulian Cultural Complex (henceforth Acheulian) is characterized by the production of small, medium and large (over 10 cm) flakes, the manufacture of bifaces, usually known as handaxes or Large Cutting Tools, and sets of core-tools (e.g., chopping tools, cleavers, spheroids/polyhedrons) and flake-tools (Sharon, 2007; Lycett and Gowlet, 2009; Machin, 2009; Sharon, 2009; Tryon and Potts, 2011; Agam et al., 2015; Shimelmitz, 2015; Sharon et al., 2011; Sharon, 2014; Agam and Barkai, 2018a; Finkel and Barkai, 2018; Goren-Inbar et al., 2018). The Acheulian handaxe appears in a vast geographical range in Africa, Europe and west and east Asia starting at around 1.8 million years ago (Bar-Yosef and Belmaker, 2010; Bar-Yosef and Belfer-Cohen, 2011; Dennel, 2011; Jiménez-Arenas et al., 2011; Lepre et al., 2011; Pappu et al., 2011). While in Europe biface manufacture and use continued into the Middle Paleolithic Mousterian (roughly 200-40/30 kya), bifaces disappear altogether from post-Acheulian, Middle Paleolithic Mousterian industries in the Levant (Hovers and Belfer-Cohen, 2013; Sharon, 2014; Hérisson and Soriano, 2020; Mathias et al., 2020) and Africa (Tryon and Faith, 2013; Richter et al. ,2017). However, some scholars point out substantial differences between Acheulian and Mousterian bifaces in Europe (e.g., Soressi, 2004; Claud, 2008; White and Pettit, 2016).

Middle Paleolithic (MP) assemblages in the Levant do not contain any "core-tools" (handaxes, cleavers and spheroids), while blanks (flakes, blades and points) were produced using various techniques. Flake-tools predominate. The Levantine MP is most prominently characterized by the use of the Levallois method, a well-studied technological system aimed at the production of well-planned and predetermined items (Boëda et al., 1995; Schlanger, 1996; Chazan, 1997; Eren and Lycett, 2012; Hovers and Belfer-Cohen, 2013; Shea, 2013). Other reduction strategies were used elsewhere alongside the Levallois (e.g., Meignen, 2000, Meignen, 2002), but in the Levant, the Levallois prevailed.

The late Acheulian sites of Revadim and Jaljulia, both in central Israel, provide a rare opportunity to study the patterns of assimilation of a technological innovation within the lithic assemblages of the Levantine Late Lower Paleolithic. The assemblages, typical of the late Acheulian Levant, are mostly dominated by flake production and flake-tools but also include handaxes (for Revadim, see, e.g., Malinsky-Buller et al., 2011; Marder et al., 2011; Rabinovich et al., 2012; Agam and Barkai, 2018a; Zupancich et al., 2018; Rosenberg-Yefet and Barkai, 2019; for Jaljulia, see Shemer et al., 2018; Rosenberg-Yefet et al., 2021; Zupancich et al., 2021; Shemer et al., submitted).

Revadim and Jaljulia contribute important new data in support of the early Lower Paleolithic origins of the Levallois method in the Levant. Our findings show that these sites might represent an early stage in the assimilation of technologies that resemble the Levallois and were rather widespread within late Acheulian archaeological sites in this region. In this paper we will present the reduction sequence of the proto-Levallois method as represented at both sites and characterize what we believe to be the early stages of its assimilation, using it as a case study to discuss broader issues of the adoption and assimilation of technological innovations during Lower Paleolithic times.

The Levallois method is a distinctive blank production method for manufacturing flakes/blades of predetermined shape and size. Careful preparation of the core in a series of removals creates the necessary core convexities and dictates the size and shape of the desired end products (Boëda et al., 1995; Schlanger, 1996; Chazan, 1997; Eren and Lycett, 2012). Examples of this widely distributed method, typically associated with *Homo heidelbergensis*, *Homo neanderthalensis*, *Homo sapiens*, *Denisovans* and other MP human groups, can be found in sites in Africa, Europe and Asia (e.g., Eren and Lycett, 2012; Adler et al., 2014; Akhilesh et al., 2018; Jacobs et al., 2019; Hu et al., 2019; Centi and Zaidner, 2021; Hershkovitz et al., 2021). As we will later show, the appearance of the Levallois method at pre-Middle Paleolithic sites indicates that it was most probably invented and assimilated by the ancestors of Middle Paleolithic hominins in the Levant.

Levallois cores are characterized by two asymmetrical platforms, separated by a plane of intersection. The lower platform has a larger volume and serves as the striking platform, while the upper platform serves as the production surface. The hierarchical relationship between the two platforms means that they cannot be switched during the reduction sequence. The Levallois concept can also be thought of as a specific organization of the volume from which a mass of material will be reduced while preserving the convexities of the platforms (Boëda et al., 1995; Van Peer, 1995). Levallois cores that can produce one flake are termed lineal\preferential cores, and those that can produce a series of flakes are termed recurrent cores. These cores are further categorized as unidirectional, bidirectional, or centripetal, in accordance with the direction of the flaking on the production surface (Inizan, 1999:61–68; Shea 2013:84–93).

Many definitions of the Levallois method have been proposed. The early definitions, influenced by Bordes's (1971) typological approach, were morphological, focused mainly on the form of the blanks. But this approach ignored the process itself: core preparation, reduction, and maintenance (Van Peer, 1995; Chazan, 1997). In the 1990s, with advances in the study of the Levallois method, a group of French archaeologists proposed a more precise definition of this technology, to which they assigned six major characteristics (Boëda et al., 1995): 1) the volume of the core is bifacial, with two distinct surfaces that intersect at the core's margin, thereby forming a "plane of intersection"; 2) the two surfaces are hierarchically related, one constituting the striking platform and the other the primary production surface; 3) the flaking surface is shaped to possess both distal and lateral convexities; 4) the blanks are removed parallel to the plane of intersection; 5) the intersection of the striking platform surface and the flaking surface is perpendicular to the flaking axis of the blank; 6) direct hard hammer percussion is used to remove the blanks.

By thus reducing the core, the knapper was able to produce two types of items: predetermined items, which are the target items (or end products), and predetermining items, which were detached during core design and maintenance. This division facilitates technological understanding but also illuminates the intention and preplanning of the knapper, with all their cognitive implications (Schlanger, 1996). The Levallois is viewed as more cognitively sophisticated than earlier methods of flint knapping practiced by Lower Paleolithic Acheulian hominins (e.g., Ambrose, 2001; Pelegrin, 2005; Haidle, 2010; Stout, 2011; Eren and Lycett, 2012; Stout et al., 2015; Wynn and Coolidge, 2016). It is thus frequently regarded as a landmark in cognitive human evolution, indicative of working memory capacity and expertise, among other qualities (Ambrose, 2001; Pelegrin, 2005; Haidle, 2010; Wynn and Coolidge, 2010; Stout, 2011; Eren and Lycett, 2012; Cole, 2015; Stout et al., 2015; Wynn and Coolidge, 2016). However, the diversity of complex prepared core methods which precedes the emergence of the fully fledged Mousterian Levallois method weakens any claims for a cognitive "jump" (Chazan, 2020).

A reconstruction of the reduction sequence reveals how these cores reached their final shape, the one usually found at archaeological sites (sometimes nicknamed "tortoise-shape" cores). The knapper focused first on the shaping of the striking platform. Most preparations were initiated at the distal and proximal ends. In some cases, the lateral edges remained almost unshaped. As the reduction process continued, the knapper focused on the proximal end of the core rather than the distal one. In the case of recurrent Levallois cores, most preparations were carried out during the first stage of core design, while later in the process, preparations were only minimal (Van Peer, 1992). The preparation stage is clearly the most important, and hence the preplanning ascribed to the method.

Humans in the Old World produced sharp-edged stone items as early as the Lomekwian and Oldowan stone tool industries in Africa (Harmand et al., 2015; Toth and Schick, 2018). Why, then, after more than two million years of flake production, did Middle Pleistocene early humans begin to produce such items by means of a complicated and sophisticated technological procedure such as Levallois (Režek et al., 2018)? Once considered a relatively wasteful production method in terms of volume removed to achieve the desired end product, the Levallois is now seen in a different light (Lycett and Eren, 2013; Shimelmitz and Kuhn, 2018). Studies over the last two decades argue that the need for certain functional advantages might have motivated people to produce items in a new way. These studies suggest that the Levallois method is in fact more efficient in terms of both stone utilization and controlling the shape and size of the end-product (Brantingham and Kuhn, 2001; Eren and Lycett, 2012; Lycett and Eren, 2013; Muller et al., 2017). A further advantage of the Levallois method is that it produces a wide and rather thin flake that extends across most of the core production surface but is also light enough for easy transport and use. Another possible advantage is in the obtuse angle between the two faces of the end product, which makes these items more resistant and durable (Eren and Lycett, 2016) while also facilitating improved handling and hafting. The relative standardization of the end products might be seen as an advantage as well (Schlanger, 1996), in terms of knapping economy and ease of hafting, key factors according to some scholars (Hérisson and Soriano, 2020). The use of technology that allows better control over the final product reduced the need for further retouch of the items after flake production (Moncel et al., 2020).

While the Levallois method was once widely viewed as a Middle Paleolithic innovation, the idea that it was practiced in the Levantine Acheulian, and especially the late Acheulian assemblages, is no longer outside the mainstream. Its roots in the Lower Paleolithic Acheulian have been demonstrated by a plethora of studies during the last four decades in sites in Africa (Rolland, 1995; Tryon, 2006; de la Torre, 2010; Wilkins et al., 2010), Europe (Villa, 2009; Despriée et al., 2010; Nowell and White, 2010; Moncel et al., 2011; Moncel et al., 2011; Rodríguez et al., 2011; Ollé et al., 2013; Picin et al., 2013; Moncel et al., 2015; Hérisson et al., 2016), the Levant (Gilead and Ronen, 1977; Goren, 1979; Ronen et al., 1980; Goren-Inbar, 1985; Chazan, 2000; DeBono and Goren-Inbar, 2001; Goren-Inbar, 2011; Shimelmitz et al., 2016; Zaidner and Weinstein-Evron, 2016; Goren-Inbar et al., 2018; Chazan 2020), and the Caucasus (Adler et al., 2014). Additionally, recent publications demonstrate that the Levallois method appears earlier than previously thought in India (Akhilesh et al., 2018) and perhaps even in China (Hu et al., 2019, although see Li et al., 2019 for reservations). We do note, however, that some researchers see the Levallois as having arrived in the Levant from outside the region, probably from Africa, linking its beginnings to the appearance of *Homo sapiens.* In this approach, its appearance in the Middle Paleolithic is thus seen as a completely new phenomenon, and not a gradual local development (Zaidner and Weinstein-Evron, 2020), as we argue in this paper.

The Levallois method also varies widely from region to region, as reflected, for example, in Levallois variants such as the Nubian and the Aduma of the Khormusan in Africa (Goder-Goldberger, 2013; Usik et al., 2013). In addition to the well-defined variants themselves, inter- and intra-site variability is common (e.g., Meignen, 1995; Tuffreau, 1995; Hovers and Belfer-Cohen, 2013; Hérisson et al., 2016; Carmignani et al., 2017; Prévost and Zaidner, 2020; Centi and Zaidner, 2021). Variability (regional or not) raises an important question regarding the ability to identify technologies at different stages of adoption. Variants at the periphery of the mainstream of the technology might be misinterpreted as stages of discovery and/or adoption. This challenging issue is, however, beyond the scope of this paper, which focus on the late Acheulian in the Levant, before the fully fledged Levallois method was practiced. Thus, the identified variants could not be mistaken for anything but early stages of adoption or assimilation.

Despite the growing consensus that the Levallois had Acheulian roots, its practice in the later terminal Lower Paleolithic Acheulo-Yabrudian cultural complex is still unresolved. The definition of the Acheulo-Yabrudian cultural complex did not originally include the use of the Levallois method as an integral part of the technological repertoire and adaptation strategy of these early humans (Barkai and Gopher, 2013; Adler et al., 2014; Gopher et al., 2005). However, some scholars have argued for the presence of some characteristics of the Levallois method at Acheulo-Yabrudian sites as well (Bar Yosef and Belmaker, 2010; Shimelmitz et al., 2016; Zaidner and Weinstein-Evron, 2016). At the Acheulo-Yabrudian site of Qesem Cave, in any case, the 200,000 years of human occupation of the site (Barkai and Gopher, 2013) show no evidence of Levallois practice, despite the very close proximity of the cave to the late Acheulian site of Jaljulia, for which we will present evidence that Levallois concepts were practiced to some extent. Therefore, although technological continuity from the terminal Lower Paleolithic late Acheulian to the Acheuleo-Yabrudian and to the Middle Paleolithic has not yet been established, the presence of Levallois concepts during this time interval remains an intriguing scenario that awaits further data and analyses.

Pre-Middle Paleolithic cores displaying Levallois characteristics are defined differently for the different sites, seriously impeding any effort to clearly portray the chrono-geographic distribution of these items. The various definitions include, for example, prepared cores, centripetal cores, mode 3 technology, hierarchical cores, radial cores, proto-Levallois cores, and more (White and Ashton, 2003; Wilkins et al., 2010; Moncel et al., 2015; Picin, 2017; Leader et al., 2018, to name but a few). To try and mitigate the confusion arising from the multiplicity of terms used to describe these items, we will consider all of them to be *prepared cores*, sharing new concepts of flake production technology, as will be described in detail later.

The actual technological origins of the Levallois are also controversial. Some see earlier core technologies as a source for the emergence of the Levallois method. The Victoria West and Tabelbala-Tachengit giant core technologies have been cited in support of this approach (Sharon, 2009), as have as the cores of the Kapthurin Formation (Tryon et al., 2005; Johnson and McBrearty, 2012). Similarly, Adler et al. (2014) see the development of Levallois method as a local evolutionary process, suggesting that "*Levallois technology is an inherent property of the Acheulian that evolves out of the existing.*" Others see the Acheulian handaxes as the technological source of origin. Handaxes characterized by a later preferential flake scar might offer evidence of a link to Levallois technologies (DeBono and Goren-Inbar, 2001; Marder et al., 2006; Goren-Inbar, 2011; Shimelmitz, 2015; Rosenberg-Yefet et al., 2021). The knapper used a bifacial flaking strategy that took advantage of the convexities on both faces of the handaxe, a concept similar to the Levallois method. Rolland (1995), however, takes the view that the Levallois method might have been discovered by accident, as a result of knapping mistakes. He suggests that the skill involved in the production of handaxes, and particularly the final stage of handaxe trimming by the detachment of thinning flakes, could have led to this "accidental" discovery. Shipton et al. (2013), on the other hand, suggest that "*Levallois technology appears to have arisen out of adapting aspects of handaxe knapping, including shaping of surfaces, the utilization of two inter-dependent surfaces, and the striking of invasive thinning flakes*". Moreover, White et al. (2011) see the combination of bifacial flaking and predetermined blank production as two elements that together provide the technological background for the invention and appearance of the Levallois method. In this same context, a recent paper (Rosenberg-Yefet et al., 2021) questioned the association of a single technological origin with the emergence of the Levallois method. The authors argued that human culture is an amalgamation of many different cultural traits as well as many innovation events. In what is known as "cumulative cultural evolution" or "the ratchet effect" (Tomasello, 1999:37; Tennie et al., 2009; Mesoudi, 2011), a technological innovation can be a combined outcome of several different technological trajectories. Hence, the Levallois method could have been invented and assimilated as the result of both handaxe technology as well as Acheulian core technologies. The existence of a "pull of knowledge" was suggested for the emergence of prepared core technologies during the early Middle Paleolithic at the site of Payre, France, where different methods (Levallois, discoid and Quina) were used in tandem and might imply a combination of different trajectories (Baena et al., 2017).

Two distribution models are generally considered in the study of the emergence and spread of significant innovations: cultural transmission versus convergent cultural evolution. The first model posits invention in one core-area that becomes widespread through social learning (Fontana et al., 2013; Groucutt et al., 2015; Lycett et al., 2016). The second model posits the invention of a technology independently in different areas, through individual learning (White et al., 2011; Wilkins and Chazan, 2012; Ollé et al., 2013; Adler et al., 2014; Shipton, 2016). The gradual, local development of a technological innovation was shown recently through the Orgnac 3 sequence for the European case (Bahain, et al., 2022). This important issue will be addressed in depth in a separate paper.

In the Levant, the adoption of prepared core technologies might also have been influenced by environmental conditions. Unlike Europe, the Levant was not heavily influenced by glacial and inter-glacial cycles (however, it is evident that other environmental conditions, related not to climate but to the availability of prey animals, changed dramatically at the end of the Lowe Plaeolithic period. This change is reflected in the transition from the consumption of very large animals in the Lower Paleolithic Acheulian (megaherbivores, specifically proboscideans) to medium and small animals in the terminal Lower Paleolithic (the Acheuleo-Yabrudian Cultural Complex, or AYCC) and the Middle Paleolithic of the southern Levant. A recent study examining faunal remains from 58 Pleistocene sites from the Levant demonstrates this dramatic decline in animal body mass but suggests that climate change had little, if any, effect on that decline (Dembitzer et al., 2022).

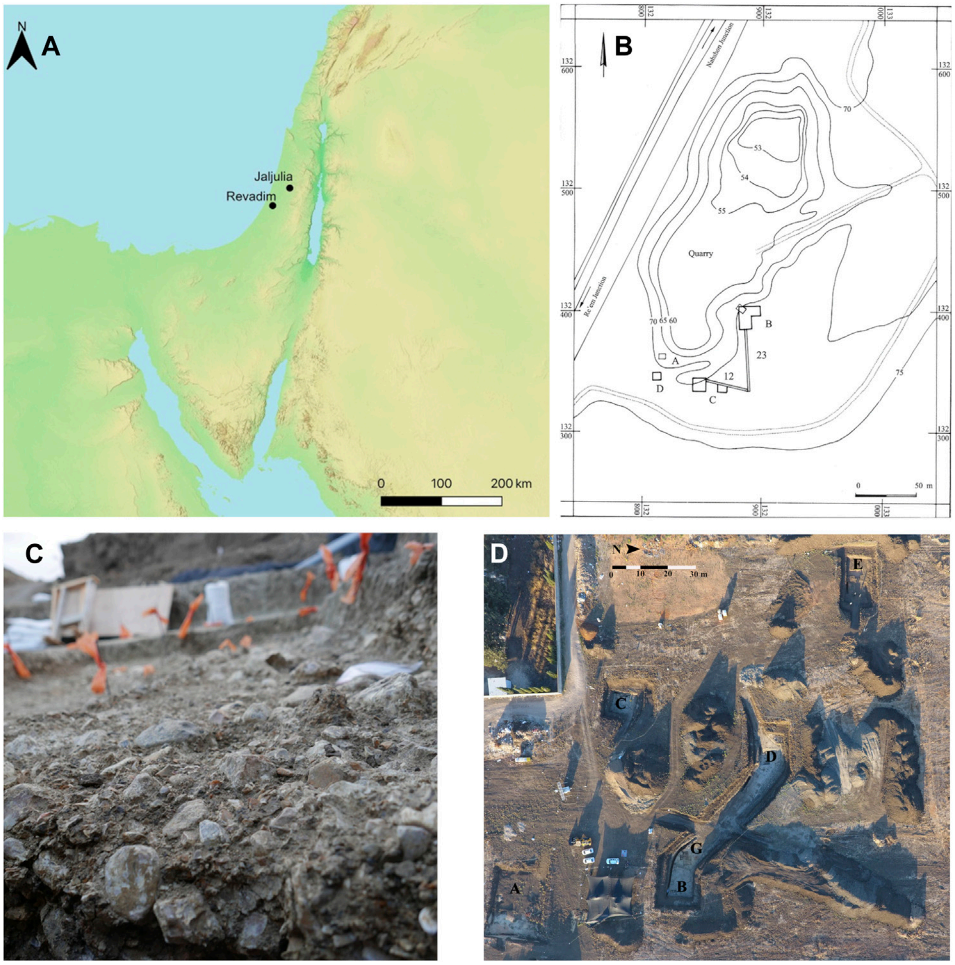

FIGURE 1 | (A) Location of the sites discussed in the text; **(B)** Revadim site areas of excavation; **(C)** A close-up at the archaeological horizon of Area B, Jaljulia. Note the high density of the flint items; **(D)** Jaljulia site areas of excavation.

Mega herbivores, and elephants in particular, provided a unique combination of fat and meat, making them the "ideal" caloric package for early humans (Guil-Guerrero et al., 2014; Guil-Guerrero et al., 2018). In addition to their high fat content, high energetic return, and significant biomass, it is suggested that early human were capable and skillful in hunting megaherbivores (Bunn and Pickering, 2010; Bunn and Gurtov, 2014; Domínguez-Rodrigo et al., 2017; Agam and Barkai, 2018b; Bunn, 2019; Ben-Dor and Barkai, 2020; Ben-Dor et al., 2021a; Ben-Dor et al., 2021b; Ben-Dor and Barkai, 2021). Proboscidean remains are indeed found at many Lower Paleolithic Acheulian sites in the Levant and beyond (e.g.,: Goren-Inbar et al., 1994; Solodenko et al., 2015; Zutovski and Barkai, 2016; Ben-Dor and Barkai ,2020a; Barkai, 2021; Konidaris and Tourloukis, 2021).

However, it appears that proboscideans played a role in Lower Paleolithic human life and cosmology well beyond their dietary importance. Archaeological and ethnographic research supports the idea that early humans in the Old and New Worlds shared habitats with other animals while perceiving them as both essential food sources and equal other-than-human entities (Tanner, 2014; Barkai, 2019; Barkai, 2021). In hunter-gatherer societies, some animals are perceived as equal partners in a relationship defined by reciprocity (Ingold, 2000; Tanner, 2014; Halfon and Barkai, 2020), although not all hunter-gatherers perceive these relationships in exactly the same way (Lewis, 2021; Tanner, 2021).

The nexus between faunal and technological transformations and/or stability during Pleistocene times has led some of us to posit a link between the hunted animals, the technology used to hunt and process them, and the cosmological perceptions of the hunters (Finkel and Barkai, 2018; Halfon and Barkai, 2020; Finkel and Barkai, 2021). In this view, early humans during Lower Paleolithic times adopted technologies suited to the hunting and processing of large herbivores. Their reasons for doing were, of course, practical, but were motivated also by cosmology (e.g., Finkel and Barkai, 2021; Dembitzer et al., 2022), reflected, for example, in the manipulation of elephant bones for bot nutritional and non-nutritional purposes, such as the use of bones for the production of bifaces (Mussi, 2005; Finkel and Barkai, 2018; Boschian et al., 2019; Barkai, 2021). When these prey animals were no longer available, the hunters adopted new technology suited to the acquisition and processing of smaller animals. Elephants disappeared from post-Acheulian sites in the Levant and so did handaxes, perhaps paving the way for new technological changes to come.

Changes in human culture as a response to changes in the environment have been proposed as a driver of technological change that might also have led to the invention and assimilation of the Levallois. In studies of east Africa, for example (Potts and Faith, 2015; Owen et al., 2018; Potts, et al., 2018), analyses of sediments from Lake Magadi (Kenya) reveal significant environmental changes around 525 to 400 ka, mainly increasing aridity, accompanied by a significant change in the fauna, mainly the local extinction of several large-bodied mammals and their replacement by smaller, related species, leading in turn to the need for new toolkits (Owen et al., 2018). Environmental changes such as these are known to create pressure on the population, forcing humans into greater mobility and therefore greater interaction between groups. That scenario can also motivate technological changes and facilitate the spread of technological knowledge (Potts et al., 2018). A study by Picin (2017) also links the invention of the Levallois method to environmental and ecological changes. According to this hypothesis, the Levallois method was a response to the changing faunal conditions, bringing early humans to increase their foraging radius and change their mobility patterns, which in turn motivated changes in core technology.

Whatever its origins, we can expect the Levallois life cycle to follow a pattern that typifies many other innovations: gradual emergence and early ascent, more widespread assimilation, and eventual domination (Henrich, 2001). We thus expect the early Levallois technology (*senso lato*) at the two late Acheulian sites of Revadim and Jaljulia to differ from its mature, full-fledged Middle Paleolithic version in terms of standardization, technological distinctiveness, and frequency of appearance. The present paper aims at capturing an intriguing phase in the adoption and spread of this technological innovation during late Acheulian times in the Levant.

2 MATERIALS AND METHODS

2.1 Archaeological Settings: Revadim and Jaljulia

Revadim is a multi-layered late Acheulian site located on the southern coastal plain of Israel (**Figure 1A**). Paleomagnetism results for the sequence exposed in the quarry showed normal polarity, indicating that the sequence is younger than 780,000 BP. Uranium-thorium analysis of carbonate covering flint items dated it to between 500,000 and 300,000 BP. During four excavation seasons, four main areas were excavated (A–D) as well as two trenches which stratigraphically connect Areas C and B. Altogether, an area of 250 m^2 was excavated, 170 m^2 were exposed in Areas A–D, and ca. 80 m^2 in Trenches 12 and 23. The analysis of the flint and faunal assemblages indicates a late Acheulian assignment of all layers of the site (see details in Gvirtzman et al., 1999; Marder et al., 1999; Marder et al., 2011; Rabinovich et al., 2012; Solodenko et al., 2015; Agam and Barkai, 2018a; Zupancich et al., 2018; Rosenberg-Yefet and Barkai, 2019; Rosenberg-Yefet et al., 2021). The rich faunal assemblage includes *Palaeoloxodon antiquus, Bos primigenius, Gazella gazelle, Capra cf.* aegagrus, and Dama cf. mesopotamica (Gvirtzman et al., 1999; Rabinovich et al., 2012).

Previous analysis of the Revadim site revealed a varied core technology that includes three main reduction sequences: 1) The production of large and medium flakes from single, double or multiple striking platform cores, 2) the production of predetermined items from prepared cores and discoid cores, and 3) the production of very small flakes by recycling of existing items as cores on flakes (Malinsky-Buller et al., 2011; Agam et al., 2015; Solodenko et al., 2015; Rosenberg-Yefet, 2016; Agam and Barkai, 2018a; Venditti et al., 2019a; Venditti et al., 2019b).

The blanks produced by these methods were sometimes further modified in different ways and constitute the largest group of tools, termed flake-tools, alongside a wide variety of bifaces and other tool types (e.g., handaxes and chopping tools) (Marder et al., 2006; Solodenko, 2010; Malinsky-Buller et al., 2011; Agam et al., 2015; Solodenko et al., 2015; Malinsky-Buller, 2016; Cohen, 2018; Rosenberg-Yefet and Barkai, 2019).

The sample chosen for this study includes prepared cores and items detached from prepared cores, originating from four different contexts of the site, representing the four lithic assemblages studied thus far. These are layers B2 and C5 (**Figure 1B**), which are the oldest contexts of the site and assumed to be rather chrono-stratigraphically contemporaneous, and layers C3 and B1, which are stratigraphically younger. All four assemblages have been initially sorted and analyzed (**Supplementary Table S1**).

Core trimming elements (CTEs), which are the products of shaping and maintaining prepared cores and originated from the studied layers (C3 and C5), were also included. These items were separated from the rest of the CTE assemblage during preliminary classification.

Jaljulia is a late Acheulian site located on the central part of the coastal plain of Israel (**Figure 1A**), some 6 km south of the late Acheulian site of Eyal and 6 km north-west of the Acheulo-Yabrudian site of Qesem Cave (Ronen and Winter 1997; Gopher et al., 2005). Approximately 80 m^2 of late Acheulian deposits were excavated during 2016–2017 in the framework of a salvage excavation by the Israel Antiquities Authority in collaboration with the Department of Archaeology at Tel-Aviv University (Shemer et al., 2018). Lithic assemblages are rich (**Figure 1C**) but faunal preservation is poor. Lithic analysis is currently in process, and therefore only preliminary observations are currently available (**Supplementary Table S2**). The assemblages are mostly dominated by flake production and flake-tools, although all include handaxes. Core technology varies and includes three main reduction sequences, very much similar to those described above for Revadim. The lithic assemblage chosen for this study, currently at the final stages of lithic analysis, was retrieved from an area of $6\,m^2$ (area B, **Figure 1D**).

2.2 Methodology

A total of 72 prepared cores from Revadim (out of a total of 1407 cores from the four assemblages, 5.1% of all cores) and a total of 105 prepared cores, including 13 core fragments, (out of a total of 602 cores, 17.4% of all cores) from Jaljulia were included in the current study, with a further subdivision into proto-Levallois cores, discoid cores, and prepared cores (general) (**Supplementary Figure S1**) for those that could not be assigned to the Levallois/discoid categories. See **Supplementary Table S3** for details.

Characterizing prepared cores is difficult due to the variety of definitions used in the literature and the lack of uniformity. While some scholars use the term "prepared cores" to describe cores similar to Levallois cores (e.g., Wilkins et al., 2010; Leader et al., 2018), we use the term more generally to include proto-Levallois cores but also other core methods. Our definition is in the spirit of Debénath and Dibble (1994:23), who defined prepared cores as "a number of technologies…in which the core was intentionally shaped or prepared in such a way as to predetermine the shapes of flakes taken from it". All cores under that definition are fully or partially centripetal in their design, in contrast to one, two or multi-platform cores. Therefore, all cores are characterized by two surfaces and a plane of intersection, although their exact role in the reduction sequence varies between sub-methods, as does the presence or absence of hierarchy between them.

Cores originating from pre-Middle Paleolithic contexts but bearing conceptual resemblance to Levallois cores are defined in very different ways by different scholars. We follow here the definition proposed by Picin (2017), whereby proto-Levallois cores are cores in which the volume is divided into two hierarchical surfaces, a striking platform and a flaking surface, with a plane of intersection separating the two surfaces. The plane of intersection is delineated by a partial or complete bifacial ridge. Striking platforms are usually roughly prepared, and lateral and distal convexities of the flaking surface are roughly configured by either *débordants* flakes or by preparational flaking of the core circumference (Picin 2017). In this study we did not define cores as fully fledged Levallois, though some of the cores do represent a more developed stage of the technology's adoption and some do meet all Boëda's criteria. The main technological difference concentrates on less strict application of the criteria. For instance, core circumference is not always prepared fully and lateral and distal convexities of the flaking surface are sometimes only roughly designed in Proto-Levallois cores.

The discoid method was the most common core technology within the prepared core category from the Lower Paleolithic onwards, although it was recognized and defined as Mousterian debitage at earlier stages of research (González-Molina et al., 2020).

On the basis of definitions by both Boëda in the mid-1990s and Terradas (2003), the criteria for identifying discoid cores were recently summarized by González-Molina et al. (2020): 1) the volume of the core is conceived in two asymmetric, secant and convex surfaces that delimit an intersection plane. 2) There is no hierarchization between the two surfaces of the core: one is conceived as a flaking surface and the other as striking platform, but with the possibility of role inversion during one operational sequence. 3) The exploitation or debitage surface is designed with a peripheral convexity that controls the knapping of each extraction. 4) The flaking axis of predetermined removals is perpendicular to the striking platform employed to obtain it. 5) The striking surface is oriented so that the intersection between both surfaces is perpendicular to the edge of the core. 6) The technique is direct percussion using a hard hammer.

Because the discoid method shares four of the six criteria described by Boëda (1993) (detailed in the introduction), further clarification is required to distinguish the two methods. The discovery and analysis of variety of discoid cores, both chronologically and geographically distributed, as part of a collection of studies by Peresani (2003), have helped researchers to resolve some of the ambiguities by distinguishing between the *sensu stricto* and *sensu lato* definitions of discoid cores (Picin and Vaquero, 2016). The term discoid *sensu lato* describes better cores that do exhibit hierarchy between the two surfaces, whereas *sensu stricto* describes cores that differ from the Levallois in the lack of hierarchy between their surfaces and in the direction of production, which is secant to the plane of intersection of the two surfaces (Picin and Vaquero, 2016). For a recent study on the distinctions between these two methods, see González-Molina et al. (2020)

Our definition of discoid cores follows the guidelines set out by Terradas, who sees the discoid flaking method as consisting of "the core exploitation in order to obtain various numbers of flakes by centripetal, recurrent and usually bifacial organization of removals. This exploitation proceeds by maintaining a strong stability of the volumetric concept of the core, which requires little specific preparation of its striking platforms and flaking surfaces. The core resulting from this sort of exploitation has an oval shape and a biconvex asymmetric section" (Terradas, 2003). These cores comply with the *sensu lato* definition, since the term refers to cores that do exhibit hierarchy between the two surfaces, which in our case are also switchable.

We analyzed the cores by weight (light, 1–49 g, medium, 50–99 g, and heavy, above 100 g), flint quality (homogeneous, fairly homogeneous, and heterogeneous), and texture (fine-grained, medium-grained, and coarse). Determining flint quality and its effect on toolmaking is challenging. While microscopic material evaluations are gaining a foothold, this is out of the scope of the current research. Therefore, here we determined flint quality and texture as visible to the naked eye. Stone quality, although a subjective criterion, was determined in this study by the homogeneity of the material and by the presence or absence of disturbances in the flint. Homogeneous flint refers to flint with no disturbances or cracks. Fairly homogeneous flint will show one or two disturbances or cracks, and heterogeneous flint will show several. A detailed analysis of prepared core flint types from Jaljulia appears in Agam et al. (submitted).

Blank types include nodules, pebbles, old cores\handaxes, flakes, and undetermined. Handaxes that were recycled as

TABLE 1 | Major attributes of proto-Levallois cores from both sites. Prefer. (Preferential); Rec. (Recurrent); centri. (centripetal); uni. (unidirectional); bidi. (bidirectional) Homoge. (Homogeneous); Hetero. (Heterogeneous) Undeter. (Undetermined).

Proto-Levallois cores	**Revadim (*n* = 36)**					**Jaljulia (*n* = 44)**				
Core exploitation	Prefer.	Rec. centri.	Rec. uni.	Rec. bidi.	-	Prefer.	Rec. centri.	Rec. uni.	Rec. bidi.	-
	25% (*n* = 9)	47% (*n* = 17)	22% (*n* = 8)	5.5% (*n* = 2)	-	31.8% (*n* = 14)	36.3% (*n* = 16)	18.1% (*n* = 8)	11.3% (*n* = 5)	
Core convexity treatment (%)	100%	75–99%	<75%	-	-	100%	75–99%	<75%	Undeter.	-
	28% (*n* = 10)	25% (*n* = 9)	47% (*n* = 17)	-	-	34% (*n* = 15)	38.6% (*n* = 17)	20.4% (*n* = 9)	6.8 (*n* = 3)	-
Angle between two core platforms (av.)	Min.	Max.	-	-	-	Min.	Max.	-	-	-
	70.8° (SD 11.4)	92° (SD 9.4)	-	-	-	63.9° (SD 9.7)	75.7° (SD 13)	-	-	-
Éclats débordants scars	Present	-	-	-	-	Present	-	-	-	-
	53% (*n* = 19)	-	-	-	-	47.7% (*n* = 21)	-	-	-	-
Striking platform preparation after production of the main items	Present	-	-	-	-	Present	-	-	-	-
	25% (*n* = 9)	-	-	-	-	34.1% (*n* = 15)	-	-	-	-
Core blank	Nodule	Pebble	Old core\handaxe	Flake	Undeter.	Nodule	Pebble	Old core\handaxe	Flake	Undeter.
	17% (*n* = 6)	31% (*n* = 11)	22% (*n* = 8)	3% (*n* = 1)	28% (*n* = 10)	36.3% (*n* = 16)	-	4.5% (*n* = 2)	6.8% (*n* = 3)	50% (*n* = 22)
Scar data (av.)	Number of shaping scars (production surface)	Number of shaping scars (striking platform)	Failed removal scars (production surface)	Failed removal scars (striking platform)	production surface scars crossing the midline	Number of shaping scars (production surface)	Number of shaping scars (striking platform)	Failed removal scars (production surface)	Failed removal scars (striking platform)	production surface scars crossing the midline
	8	9.2	2.9	3.2	78 (*n* = 28)	11.1	12.9	3	2.6	88.6% (*n* = 39)
Cortex (striking platform)	0	1–24%	25–50%	-	-	0	1–24%	25–50%	-	-
	3% (*n* = 1)	33% (*n* = 12)	65% (*n* = 23)	-	-	18.1% (*n* = 8)	54.5% (*n* = 24)	25.5% (*n* = 11)	-	-
Cortex (production platform)	0	1-24%	25-50%	-	-	0	1-24%	25-50%	-	-
	97% (*n* = 35)	3% (*n* = 1)	-	-	-	90.9% (*n* = 40)	9% (*n* = 4)	-	-	-
Flaked patina surfaces on the core	Present	-	-	-	-	Present	-	-	-	-
	33.3% (*n* = 12)	-	-	-	-	2.2% (*n* = 1)	-	-	-	-
Core weight (gm)	Light (1–49)	Medium (50–99)	Heavy (above 100)	-	-	Light (1–49)	Medium (50–99)	Heavy (above 100)	-	-
	69% (*n* = 25)	17% (*n* = 6)	14% (*n* = 5)	-	-	46.5% (*n* = 20)	30.2% (*n* = 13)	25.5% (*n* = 11)	-	-
Flint quality	Homoge.	Fairly homoge.	Hetero.	-	-	Homoge.	Fairly homoge.	Hetero.	-	-
	47% (*n* = 17)	11% (*n* = 4)	42% (*n* = 15)	-	-	34% (*n* = 15)	34% (*n* = 15)	27.2% (*n* = 12)	-	-

TABLE 2 | Major attributes of discoid cores from both sites. Alter. (Alternate); Switch. (Switchable hierarchy); Undeter. (Undetermined); Prefer. (Preferential); Rec. (Recurrent); centri. (centripetal); uni. (unidirectional); bidi. (bidirectional) Homoge. (Homogeneous); Hetero. (Heterogeneous).

Discoid cores	**Revadim (*n* = 24)**					**Jaljulia (*n* = 35)**				
Core sub type	Alter.	Switch.	-	-	-	Alter.	Switch.	Undeter.	-	-
	66.6% (*n* = 16)	33.3% (*n* = 8)	-	-	-	71.4% (*n* = 25)	25.7% (*n* = 9)	2.8% (*n* = 1)	-	-
Core exploitation	Prefer.	Rec. centri.	Rec. uni.	Rec. bidi.	-	Prefer.	Rec. centri.	Rec. unidi.	Rec. bidi.	Undeter.
	-	83% (*n* = 20)	16.6% (*n* = 4)	-	-	5.7% (*n* = 2)	82.8% (*n* = 29)	5.7% (*n* = 2)	-	5.7% (*n* = 2)
Core convexity treatment (%)	100%	75–99%	<75%	-	-	100%	75–99%	<75%	Undeter.	-
	50% (*n* = 12)	33.3% (*n* = 8)	16.6% (*n* = 4)	-	-	31.4% (*n* = 11)	37.1% (*n* = 13)	25.7% (*n* = 9)	8.5% (*n* = 3)	-
The angle between two core platforms (av.)	Min.	Max.	-	-	-	Min.	Max.	-	-	-
	77.1° (st.d 11.3)	96.4° (st.d 9.2)	-	-	-	80.6° (SD 13.6)	89.7° (SD 11.5)	-	-	-
Éclats débordants scars	Present	-	-	-	-	Present	-	-	-	-
	37.5% (*n* = 9)	-	-	-	-	25.7% (*n* = 9)	-	-	-	-
Core blank	Nodule	Pebble	Old core\handaxe	Flake	Undetermined	Nodule	Pebble	Old core\handaxe	Flake	Undeter.
	4% (*n* = 1)	20.8% (*n* = 5)	37.5% (*n* = 9)	4% (*n* = 1)	33.3% (*n* = 8)	40% (*n* = 14)	5.7% (*n* = 2)	17.1% (*n* = 6)	2.8% (*n* = 1)	31.4% (*n* = 11)
Scar data (av.)	Number of shaping scars		Failed removal scars		Scars crossing the midline	Number of shaping scars		Failed removal scars		Scars crossing the midline
	7–8		3–4		29.2% (*n* = 7)	9–10		2–4		51.4% (*n* = 18)
Cortex on both surfaces	0	1–24%	25–50%	-	-	0	1–24%	25–50%	-	-
	33.3% (*n* = 8)	33.3% (*n* = 8)	33.3% (*n* = 8)			22.8% (*n* = 8)	28.5% (*n* = 10)	48.5% (*n* = 17)		
Flaked patina surfaces	Present	-	-	-	-	Present	-	-	-	-
	93% (*n* = 13)	-	-	-	-	11.4% (*n* = 4)	-	-	-	-
Core weight (g)	Light (1–49)	Medium (50–99)	Heavy (above 100)	-	-	Light (1–49)	Medium (50–99)	Heavy (above 100)	-	-
	45.8% (*n* = 11)	16.6% (*n* = 4)	37.5% (*n* = 9)	-	-	28.5% (*n* = 10)	25.7% (*n* = 9)	45.7% (*n* = 16)	-	-
Flint quality	Homoge.	Fairly homoge.	Hetero.	-	-	Homoge.	Fairly homoge.	Hetero.	-	-
	12.5% (*n* = 3)	37% (*n* = 9)	50% (*n* = 12)	-	-	20% (*n* = 7)	34.2% (*n* = 12)	45.7% (*n* = 16)	-	-
Flint texture	Fine	Medium	Coarse	-	-	Fine	Medium	Coarse	-	-
	20.8% (*n* = 5)	50% (*n* = 12)	29% (*n* = 7)	-	-	42.8% (*n* = 15)	48.5% (*n* = 16)	8.5% (*n* = 3)	-	-

cores while undergoing some modifications were included here, whereas handaxes with a preferential flake scar having minimal preparations were not included in the core category and are not part of the current study (see Rosenberg-Yefet et al., 2021 for a detailed description of these items). The presence of cortex on the striking platform and on the production surface was also noted, as was the presence of flaked patinated surfaces as an indication for the use of old flaked items as cores. Scar characteristics include the number of shaping scars on the production surface, the number of shaping scars on the striking platform, and the number of unsuccessful removal scars on each surface. Unsuccessful removals were determined by scars with hinge or step termination, scars indicating an angle which damaged core morphology, or scars that differ from the others in shape, depth or thickness. Scars that cross the midline of the production surface were also indicated. The minimum and maximum angles between the two platforms of the cores were measured. Core convexities were estimated (% of the core circumference). The presence of *éclats débordants* scars was noted, as were indications of striking platform preparation following the detachment of predetermined blanks. (By this we mean preparations that appear to have been made in the process of

TABLE 3 | Major attributes of prepared cores (general) from both sites. Prefer. (Preferential); Rec. (Recurrent); centri. (centripetal); uni. (unidirectional); bidi. (bidirectional); Homoge. (Homogeneous); Hetero. (Heterogeneous) Undeter. (Undetermined).

Prepared cores	**Revadim (*n* = 9)**					**Jaljulia (*n* = 13)**				
Core exploitation	Prefer.	Rec. centri.	Rec. unidi.	-	-	Prefer.	Rec. centri.	Rec. unidi.	Rec. bidi.	Undeter.
	33.3% (*n* = 3)	55.5% (*n* = 5)	11.1% (*n* = 1)	-	-	15.3% (*n* = 2)	53.8% (*n* = 7)	15.3% (*n* = 2)	7.6% (*n* = 1)	7.6% (*n* = 1)
Core convexity treatment (%)	100%	75–99%	<75%	-	-	100%	75–99%	<75%	Undetermined	-
	33.3% (*n* = 3)	33.3% (*n* = 3)	33.3% (*n* = 3)	-	-	23% (*n* = 3)	38.4% (*n* = 5)	15.3% (*n* = 2)	7.6% (*n* = 3)	-
The angle between two core platforms (av.)	Min.	Max.	-	-	-	Min.	Max.	-	-	-
	72.5	91.8	-	-	-	61.3° (SD 9.3)	70.8° (SD 13.5)	-	-	-
Éclats débordants scars	Present	-	-	-	-	Present	-	-	-	-
	33.3% (*n* = 3)	-	-	-	-	53.8% (*n* = 7)	-	-	-	-
Scar data (av.)	Number of shaping scars (production surface)	Number of shaping scars (striking platform)	Failed removal scars on the production surface	Failed removal scars (striking platform)	Production surface scars crossing the midline	Number of shaping scars on the production surface	Number of shaping scars (striking platform)	Failed removal scars (production surface)	Failed removal scars (striking platform)	production surface scars crossing the midline
	7.8	7.1	2.7	2.8	44.4% (*n* = 4)	8.1	12.6	1.6	3	92.3% (*n* = 12)
Cortex (striking platform)	0	1-24%	25-50%	-	-	0	1-24%	25-50%	-	-
	11.1% (*n* = 1)	33.3% (*n* = 3)	55.5% (*n* = 5)	-	-	53.8% (*n* = 7)	46.2% (*n* = 6)	-	-	-
Cortex (production platform)	0	1–24%	25–50%	-	-	0	1–24%	25–50%	-	-
	100% (*n* = 9)	-	-	-	-	92.3% (*n* = 12)	7.6% (*n* = 1)	-	-	-
Flaked patina surfaces	Present	-	-	-	-	Present	-	-	-	-
	22.2% (*n* = 2)	-	-	-	-	7.6% (*n* = 1)	-	-	-	-
Core weight (gm)	Light (1–49)	Medium (50–99)	Heavy (above 100)	-	-	Light (1–49)	Medium (50–99)	Heavy (above 100)	-	-
	55.5% (*n* = 5)	33.3% (*n* = 3)	11.1% (*n* = 1)	-	-	69.2% (*n* = 9)	30.7% (*n* = 4)	-	-	-
Flint quality	Homoge.	Fairly homoge.	Hetero.	-	-	Homoge.	Fairly homoge.	Hetero.	-	-
	44.4% (*n* = 4)	22.2% (*n* = 2)	33.3% (*n* = 3)	-	-	53.8% (*n* = 7)	30.7% (*n* = 4)	7.6% (*n* = 1)	-	-
Flint texture	Fine	Medium	Coarse	-	-	Fine	Medium	Coarse	Undetermined	-
	77.7% (*n* = 7)	11.1% (*n* = 1)	11.1% (*n* = 1)	-	-	76.9% (*n* = 10)	15.3% (*n* = 2)	-	7.6% (*n* = 1)	-

producing another item but the core was abandoned before that item was produced.) The core exploitation method (preferential, recurrent centripetal, recurrent unidirectional, or recurrent bidirectional) was also indicated. The detailed criteria are listed in **Table 1**, **Table 2**, and **Table 3**.

CTEs were categorized as either CTEs removed from prepared cores or éclats débordants, with the latter category further subdivided into *éclats débordants, éclats débordants a dos limité*, *and éclats outrepassés*. CTES removed from prepared cores are items for which part of the intersecting ridge between the two platforms was removed, most probably in an effort to maintain core convexities throughout the reduction sequence. These items do not fully conform to the definition of the specific CTEs detailed below.

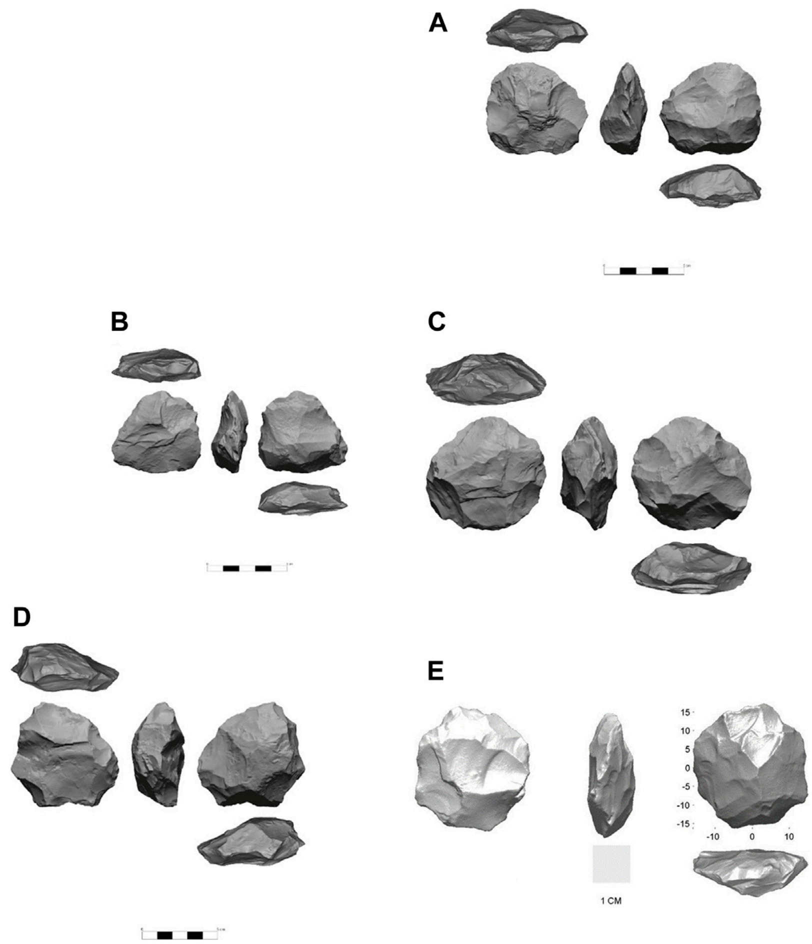

FIGURE 2 | Proto-Levallois centripetal **(A–C)** and preferential **(D,E)** cores from Revadim. Note the scars on the production surfaces indicating *débordant* removals **(A,D,E)**. **(E)** Note the extremely small size of the core. The striking platform is shown in the left part of each figure.

The *éclats débordants* items are defined as follows:

Éclats débordants (**Supplementary Figure S2A**): The terminology is drawn from similar items used in the application of the Middle Paleolithic Levallois method (Beyries and Boëda, 1983; Geneste, 1985:230; Meignen, 1995:280). It describes items removed from the lateral edge of a core during the shaping and maintenance of the production surface, mostly between production phases. Part of the bifacially shaped plane of intersection that separated the production surface from the striking platform was also removed (Boëda, 1993). Such removals took place during relatively advanced stages of the Levallois reduction sequence (Hovers, 2009:82).

Éclats débordants a dos limité (**Supplementary Figure S2B**), also termed pseudo-Levallois flakes: These items were produced during advanced stages of Levallois core reduction (Boëda et al., 1990:68; Hovers, 2009:82) and were removed from the core in order to correct irregularities in the morphology of the production surface, thus contributing to the maintenance of lateral convexities during the different phases of the Levallois reduction sequence (Boëda et al., 1990).

Éclats outrepassés (**Supplementary Figure S2C**). "These were detached only when intensive use of both the striking platform and the flaking surface of the core had distorted the geometry of the flaking surface. Rejuvenation of the lateral and (mainly) distal convexities required removal of the exploited surface and extensive rearrangement of the flaking surface. Such items are expected to show a large number of dorsal face scars and a complex dorsal face scar pattern" (Hovers, 2009:82).

Similarities between CTEs removed from prepared cores and items removed from handaxes during their different manufacturing stages are also noteworthy. These similarities, mainly in dorsal scar pattern and the removal of parts of the bifacial ridge, make it difficult to distinguish between these two categories (Copeland, 1995; Goren-Inbar et al., 2018).

CTEs were analyzed according to the following parameters: metric measurements (maximum length and width), scar pattern (centripetal, unidirectional, or bidirectional) and number of scars, platform preparation type (plain, punctiform, faceted, dihedral, linear, or undetermined), interior and exterior platform angle (IPA and EPA, respectively), ridge angle, cross section type (obtuse triangle, isosceles trapezoid, parallelogram, equilateral

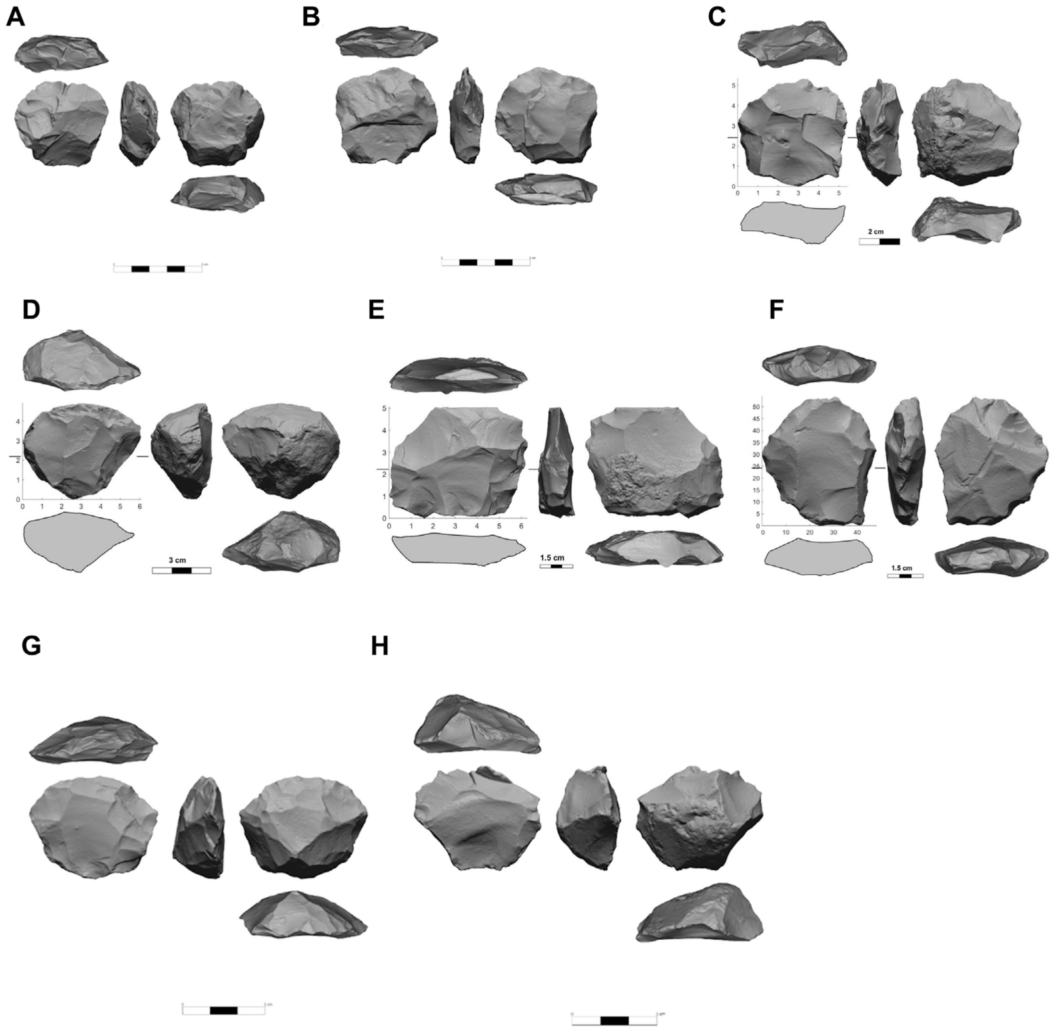

FIGURE 3 | Proto-Levallois centripetal **(A–F)** and preferential **(G–H)** cores from Jaljulia. Note the scars on the production surfaces indicating *débordant* removals **(C,E,F,H)**. The striking platform is shown in the left part of each figure.

triangle, right triangle), and end termination (feather, overshot, hinge, retouched, or unclear).

For the platform angles, we followed Dibble and Whittaker (1981: 286), who define IPA as "the angle formed between the platform surface and a line through the point of percussion to the base of the bulb" and EPA as "measured at the intersection of the platform surface and the exterior surface of the core" (**Supplementary Figure S3**).

Blanks produced from prepared cores are predetermined items that were detached from prepared cores. It seems that these blanks were not produced for the purpose of shaping or maintaining the core; we thus view them as the desired end-products of the knapping process. They usually exhibit a larger IPA than the regular flakes, and their striking platforms are usually shaped, faceted, or dihedral. Their dorsal scar pattern varies, but it is either centripetal or unidirectional. If unidirectional, it differs from the scar pattern that we see in these sites for the regular flakes. These items were retrieved from all other categories (shaped and unshaped items) following the identification of particular characteristics (shaped striking platform, scar pattern, curvature, and so forth). Items detached from prepared cores were analyzed according to the following parameters: metric measurements (including thicknesses in the bulb area, middle and end of the flake), scar pattern and number of scars, platform preparation type, IPA and EPA, and end termination.

3 RESULTS

3.1 Characteristics of the Three Prepared Core Sub-types From Revadim and Jaljulia

3.1.1 Proto-Levallois Cores

(**Supplementary Figure S4**): The major attributes and metrics of the proto-Levallois cores are presented in **Table 1**. All cores exhibit full/partial bifacial shaping of their circumference,

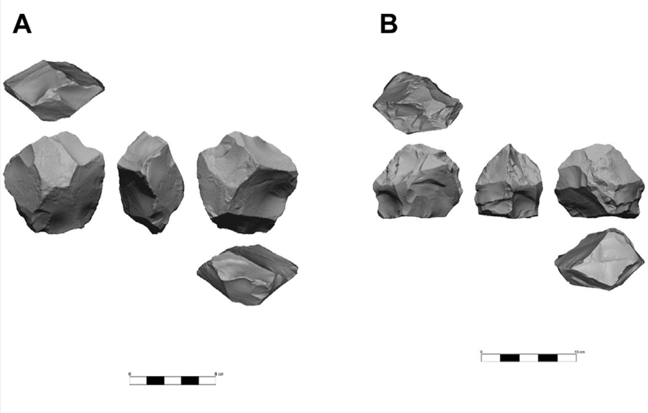

FIGURE 4 | Discoid alternate cores from Revadim.

delineating the plane of intersection, and a clear hierarchy between the striking platform and the production surface. Scars on the production surface reflect blanks removed in parallel to the plane of intersection. Cores were exploited mostly in the centripetal (**Figures 2A–C**; **Figures 3A–F**) or preferential (**Figures 2D–E**; **Figures 3G–H**) methods and less frequently unidirectionally or bidirectionally. Core convexities were maintained either by removing *éclats débordants* items or, alternatively, by shaping the entire circumference of the core or part of it. Scars indicating *éclats débordants* removals were observed on half of the cores (**Figures 2A,D,E**; **Figures 3C,E,F,H**). Scars indicating shaping of the entire circumference were observed on some of the Revadim and Jaljulia cores, and scars indicating shaping of part of the circumference were observed on most of the cores in both sites. Removals originating from the production surface towards the striking platform following the production of desired end products are evident in quarter of the Revadim proto-Levallois cores and one-third of the Jaljulia cores (**Figure 3E**). This phenomenon is not, by strict Levallois definition, an integral part of the method. We believe these removals could reflect some degree of striking platform maintenance between core production cycles and/or an attempt to produce additional blanks after production of the predetermined blanks. In any case, this subsequent stage of flake detachment distinguishes these late Acheulian proto-Levallois cores from MP Levallois cores.

The cores were shaped from nodules, pebbles/cobbles, old cores\handaxes, flakes, or undetermined items (**Table 1**). Cases where the blank was defined as a former core\handaxe reflect the recycling of old items into cores. The knappers of both sites occasionally selected and collected old items, in these cases old cores or handaxes covered with patina, and used them as blanks for proto-Levallois cores. This was determined based on patina differences between the two stages of use, differences in scar morphology between the stages, or both.

The Revadim proto-Levallois cores show an average of eight removal scars on the production surface and nine on the striking platform, whereas the Jaljulia cores show an average of 11 removal scars on the production surface and 13 on the striking platform. Failed removals are visible both on the production surface and on the striking platform. Scars on the production surface that cross the midline are visible on most coresin both sites. Cortex is rarely present and is restricted mostly to the striking platform (**Table 1**). Only one Revadim core and four Jaljulia cores show some cortex on the production surface.

Flint quality for these cores varied at both sites. A significant number in both sites are made of homogeneous flint and the rest are fairly homogeneous or heterogeneous. As for texture, some of the cores are made from fine-grained flint, while the rest are medium- or coarse. Nevertheless, obstacles visible in the flint that might have been the reason for core abandonment are evident in only two of the Revadim cores and four of the Jaljulia cores.

Metric measurements show that the Jaljulia proto-Levallois cores are larger and produced larger items than the Revadim cores (**Supplementary Table S4**). The extent of exploitation of the production surface of the cores is quite similar for both sites.

3.1.2 Discoid Cores

Discoid cores: The major attributes and metrics of the discoid cores from Revadim and Jaljulia are presented in **Table 2**. These cores either exhibit full\partial shaping of the circumference with no hierarchy between the two core platforms, also termed alternate cores (**Figure 4**; **Figures 5A–F**), or they exhibit a switchable hierarchy (**Figure 5F**). Most of the cores are the former type: the removals were alternated between the two surfaces in the course of the reduction sequence. The remaining cores were the latter type, exploited by switching between the platforms, as a striking platform became a production surface and vice versa. Core convexities were maintained by shaping the entire circumference of the core, or part of it. *Éclats débordants a dos limité* scars are visible on some of the cores (**Figures 5A,F**). These flakes were removed from the core in order to correct irregularities in the production surface morphology (Boëda et al., 1990). Cores were made of nodules, pebbles/cobbles, old cores\handaxes (**Supplementary Figure S5**), flakes, or undetermined items (**Table 2**).

The Revadim cores show an average of seven to eight removal scars on each surface and nine to ten for the Jaljulia cores. Failed removals (as defined above) are visible on both surfaces. Unlike classic MP discoid cores, some cores bear scars that cross the midline of the production surface. When cortex is present on the cores, it is found mostly on the striking platform. Some cores bear no cortex, some bear 1–24% cortex, and some 25–50% cortex. Flaked patinated surfaces, indicating a time lag between the two use cycles of the core, are visible on most of the Revadim cores but are rather rare at Jaljulia. Flint quality varied for both sites: some of the cores are made from homogeneous flint, while the rest are fairly homogeneous or heterogeneous in about half of the cores. As for texture, some of the cores are made of fine-grained flint, and the rest are medium-grained, in about half of the cores, or coarse. Nevertheless, disturbances in the flint that might have been the reason for core abandonment were observed in only four (16.6%) cases at Revadim and one case at Jaljulia.

The metric data in **Supplementary Table S4** shows that the discoid cores are symmetrical, to some extent, in length and

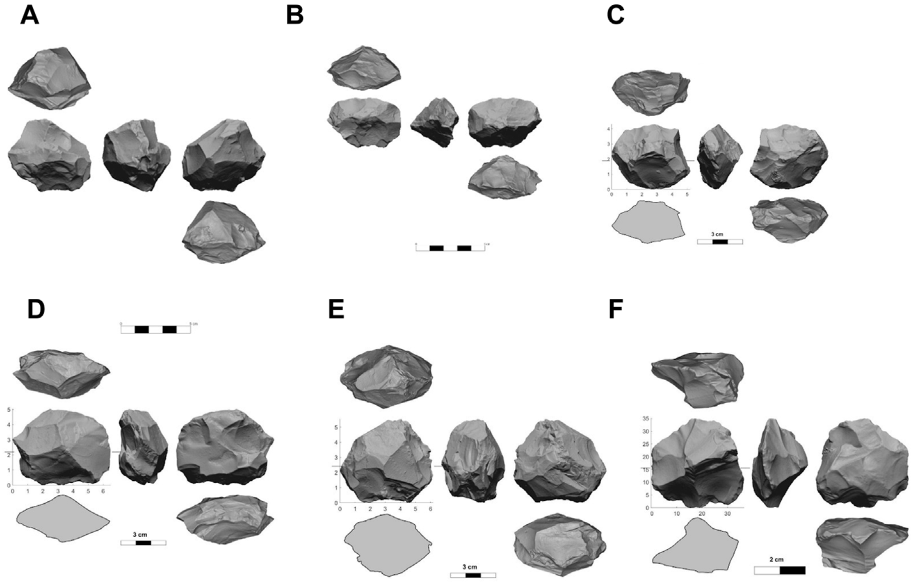

FIGURE 5 | Discoid alternate **(A–E)** and switchable hierarchy **(F)** cores from Jaljulia.

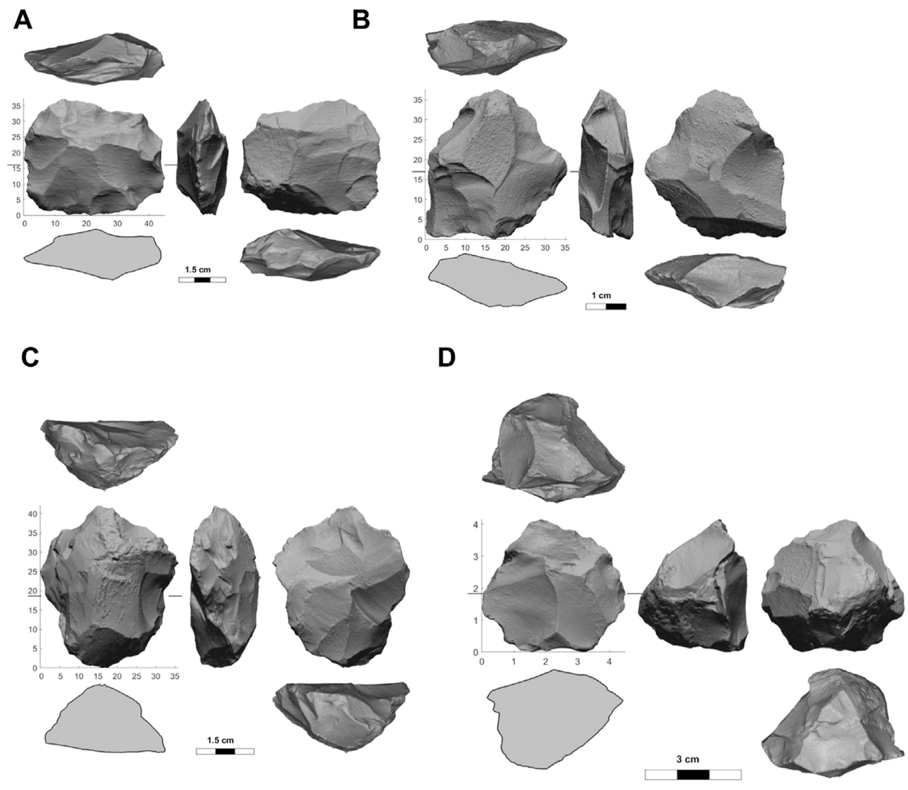

FIGURE 6 | (A–D) Prepared cores (general) from Jaljulia.

width, a property that results from the convexities having been treated around the periphery of the core. Discoid cores bear fewer *éclats débordants a dos limité* scars than the proto-Levallois cores (in which the *débordant* scars are of the type shown in **Supplementary Figure S2A**). In addition, as expected, discoid cores produced smaller items than the proto-Levallois cores and exploit the surface to a lesser degree. The degree of exploitation of discoid cores is similar for both sites (Revadim: 54%; Jaljulia: 55%).

3.1.3 Prepared Cores (General)

The major attributes and metrics of these prepared cores are presented in **Table 3** and **Supplementary Table S4**. These cores do not fully conform to the abovementioned proto-Levallois and discoid definitions, although they do exhibit two platforms, with or without hierarchy (Revadim: hierarchy, 100%; Jaljulia: hierarchy, 50%; without hierarchy, 50%), and a bifacially shaped ridge intersecting the platforms to a certain degree (usually not along the entire core circumference). These cores were reduced centripetally in half of the cores (**Figure 6**), preferentially, unidirectionally, bidirectionally, or in an unclear manner. Core convexities were maintained by shaping the entire circumference of the core, or part of it. *Éclats débordants a dos limité* scars are visible on one-third of the Revadim cores and half of the Jaljulia cores.

Cores show an average of eight removal scars on the production surface and seven on the striking platform in the Revadim case, and an average of eight removal scars on the production surface and 12.6 on the striking platform for Jaljulia. Failed removals are visible both on the production surface and on the striking platform. Almost half of the cores in Revadim and most of the cores in Jaljulia exhibit scars on the production surface that cross the midline of the surface. Cortex is rather rare and is present mainly on the striking platform. The Jaljulia cores bear less cortex than the Revadim cores (**Table 3**).

Flaked patinated surfaces, indicating a time lag between the two use cycles of the core, are rather rare.

Flint quality varied for both sites: about half of the cores are made from homogeneous materials, while the rest are fairly homogeneous or heterogeneous. As for texture, the majority of cores at both sites are made of finely textured flint while the rest are almost equally divided into medium or coarse texture (**Table 3**). However, it should be noted that flint quality appears to be the reason for abandonment in only one case at Revadim and one case at Jaljulia.

We additionally defined three roughout items from the Revadim assemblage as prepared cores: these are cores that might have been in the process of being shaped but were abandoned during quite early stages of the reduction sequence. For one item the reason for abandonment is not clear, while the other two exhibit scars resulting from unsuccessful removals that likely resulted in their abandonment. These cores bear a high percentage of cortex on both platforms and were not included in the analysis presented here. However, their presence supports our contention that prepared cores were indeed shaped and reduced on-site.

An analysis of the length and width of the production surfaces revealed no significant differences for the three core groups at Revadim. The length and width of the Jaljulia core production surfaces differ slightly, as proto-Levallois cores are a bit larger than discoid and prepared cores (general). The Revadim cores are slightly smaller than the Jaljulia cores, and all three core groups seem to represent the same size distribution (calculated by comparing the standard deviation to the average; see **Supplementary Table S4**) The picture for Jaljulia is more complex, as proto-Levallois cores are somewhat less standard in size (as can be seen by the broader statistical distribution) than the two other core groups in the assemblage.

The angle between the two core platforms displayed by the proto-Levallois cores from both sites is more acute than for the discoid cores (**Figure 7**), as expected from the core definitions. In addition, the angle between the two platforms is generally more acute for the Jaljulia than the Revadim cores. This might indicate more stringent technological standards when applying the Levallois concepts and mastery of the skills required. However, we believe that the skill level manifested in the different lithic trajectories most probably reflects decision-making for site-specific tasks rather than a more general level of capabilities and knowhow. This conclusion is based on preliminary analysis of bifaces from both sites, which revealed a heavier investment in workmanship at Revadim as opposed to Jaljulia (Zupancich et al., 2021). The much smaller difference between the minimum and maximum angles between the two surfaces, for all three core groups in the Jaljulia assemblage (**Figure 7**), might indicate high knapping skill level at the site for this line of production. We can reasonably assume that a small difference between the minimum and maximum angles is indicative of a well-prepared core that will promote fewer knapping mistakes. And vice versa, the larger difference between the minimum and maximum angles at Revadim might indicate that knapping was less meticulous, as reflected in flakes removed at unsuitable angles. However, in the case of the proto-Levallois cores, the asymmetrical angles between the two platforms at the lateral and proximal edges, mostly when *débordant* removals were applied, might complicate our ability to fully interpret these angle differences.

Regarding the proto-Levallois cores, at Jaljulia a greater number were made of undetermined blanks than at Revadim (**Table 1**), a difference possibly related to the rock types available in the vicinity of the two sites, which are characterized by different topographies.

The proto-Levallois cores from both assemblages were produced from more homogeneous and more finely textured flint than the discoid cores. However, the Jaljulia proto-Levallois cores show higher percentages of finely textured material than do those from Revadim, and the discoid cores from Jaljulia were produced from more homogeneous and finely textured flint than were the Revadim discoid cores. Thus, the Jaljulia knappers might have placed greater emphasis on material selectivity.

When low quality flint bearing visible disturbances was used, attempts were made to overcome these obstacles, as can be seen on some of the cores and CTEs. For example, some CTEs bear signs of flint disturbances on the dorsal face of the flake, suggesting that it was removed to get rid of the obstacle and allow further knapping (e.g., **Figure 9C**). A detailed study, including petrographic analysis of prepared core flint types from Jaljulia, further supports the trend we identified here that homogeneous flint was more common in the proto-Levallois cores than in the discoid cores (Agam et al., submitted).

To evaluate patterns of flint selectivity, we further compared the proto-Levallois cores from Revadim to a sample of ~300 regular one/two striking platform cores from Revadim layer C3 (**Table 4**). Flint

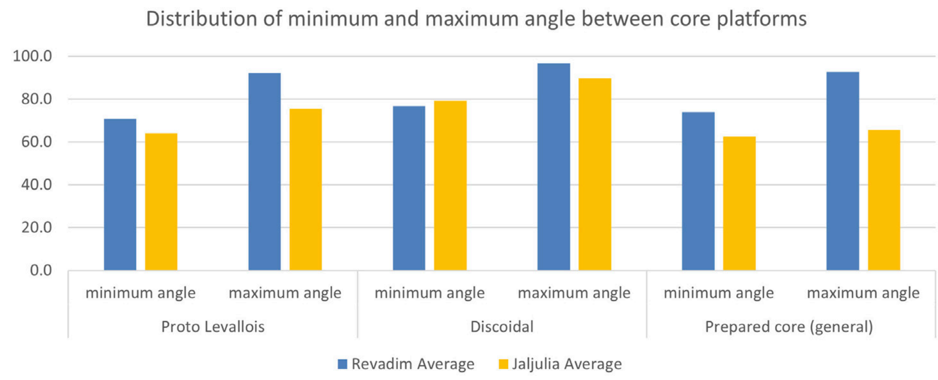

FIGURE 7 | Distribution of minimal and maximal angles between two core platforms for each method at both sites.

TABLE 4 | Distribution of flint quality for one and two striking platform cores at Revadim layer C3 as compared to prepared cores from the Revadim assemblages used in our study.

Flint quality	C3 - regular cores	Proto- Levallois cores	Discoid cores	Prepared cores (general)
	% out of the total	% out of the total	% out of the total	% out of the total
Homogeneous	35% (*n* = 103)	47% (*n* = 17)	12.5% (*n* = 3)	44.4% (*n* = 4)
Fairly homogeneous	23% (*n* = 68)	11% (*n* = 4)	37% (*n* = 9)	22.2% (*n* = 2)
Heterogeneous	42% (*n* = 125)	42% (*n* = 15)	50% (*n* = 12)	33.3% (*n* = 3)
Total	100% (*n* = 296)	100% (*n* = 36)	100% (*n* = 24)	100% (*n* = 9)
Flint texture	**% out of the total**	**% out of the total**	**% out of the total**	**% out of the total**
Fine	40% (*n* = 117)	31% (*n* = 11)	20.8% (*n* = 5)	77.7% (*n* = 7)
Medium	39% (*n* = 115)	36% (*n* = 13)	50% (*n* = 12)	11.1% (*n* = 1)
Coarse	22% (*n* = 64)	31% (*n* = 11)	29% (*n* = 7)	11.1% (*n* = 1)
Total	100% (*n* = 296)	100% (*n* = 35)	100% (*n* = 24)	100% (*n* = 9)

type analysis of the Jaljulia regular cores is not yet available, so this analysis was conducted for the Revadim assemblage only at this stage. The results indicate a preference for coarse-grained flint for both the proto-Levallois and discoid cores, in contrast to the sample of regular cores, where the preference is for finely textured, and medium textured flint. Whether the Revadim knappers preferred specific characteristics of flint homogeneity and texture for the production of prepared cores will be further evaluated in the future using a larger sample from both sites.

While the Jaljulia cores very infrequently exhibit patinated surfaces, the Revadim cores were more frequently produced from "old" patinated cores/blanks in more than one life cycle, for all core groups. This phenomenon was recently documented for the site of Gesher Benot Ya'aqov as well (Goren-Inbar et al., 2018: 231). Although we did identify the presence of these two life cycles, we could not further ascertain whether these items represented a former handaxe or a former core. In any case, whether their original function changed (from handaxe to core) or remained the same (old core to new core), this phenomenon indicates recycling of old items (Vaquero et al., 2015; Lemorini et al., 2016; Agam and Barkai, 2018a; Efrati et al., 2019; Venditti et al., 2019a).

The small number of patinated cores in our Jaljulia sample is also striking when compared to the general sample of cores of all categories from area B at Jaljulia (Bar Efrati, personal communication). In the general sample (*n* = 503), patinated cores are well represented (22.07%; *n* = 111), in sharp contrast to the prepared core category, where patination was observed on only 2.2% of the proto-Levallois cores and 11.4% of the discoid cores. The difficulty of shaping a prepared core from an old core might explain this phenomenon, whereas simple flake removal could have been executed with much less effort from an old patinated core.

Moreover, the rather meticulous shaping process required to produce a prepared core would necessitate the use of a fairly large nodule/chunk in order to allow the removal of a significant number of shaping flakes. An old shaped core would probably not have been suitable for the initiation of this shaping process. The exception to this rule is the use of "old", sometime patinated, handaxes as blanks for the production of predetermined blanks. As has been previously demonstrated, the knappers of Revadim and Jaljulia took advantage of handaxe convexities as a "shortcut" in the reduction sequence, enabling the detachment of predetermined blanks with minimal preparatory steps (Rosenberg-Yefet et al., 2021) while simultaneously shaping prepared cores anew from fresh nodules/

TABLE 5 | Major attributes of the two CTE types from both sites. Prefer. (Preferential); Rec. (Recurrent); centri. (centripetal); uni. (unidirectional); bidi. (bidirectional); Undeter. (Undetermined).

CTE	Revadim (*n* = 21)					Jaljulia (*n* = 60)						
Éclats débordants (n = 11)	-	-	-	-	-	*Éclats débordants (n = 20)*	-	-	-	-	-	-
Sub- type	*Éclats débordants*	*Éclats débordants a dos limité*	*Outrepassé*	-	-	Sub-type	*Éclats débordants*	*Éclats débordants a dos limité*	*Outrepassé*	-	-	-
	9% (*n* = 1)	63.6% (*n* = 7)	27% (*n* = 3)	-	-		-	95% (*n* = 19)	5% (*n* = 1)	-	-	-
Scar pattern (dorsal face)	Centri.	Unidi.	Bidi.	-	-	Scar pattern (dorsal face)	Centri.	Unidi.	Bidi.	-	-	-
	100% (*n* = 11)	-	-	-	-		85% (*n* = 17)	10% (*n* = 2)	5% (*n* = 1)	-	-	-
Scars number (av.)	7	-	-	-	-	Scars number (av.)	5.3	-	-	-	-	-
Striking platform preparation	Plain	Punctiform	Faceted	Undetermined	-	Striking platform preparation	Plain	Punctiform	Faceted	Undeter.	Dihedral	Linear
	54.5% (*n* = 6)	18% (*n* = 2)	18% (*n* = 2)	9% (*n* = 1)	-		15% (*n* = 3)	10% (*n* = 2)	45% (*n* = 9)	-	15% (*n* = 3)	10% (*n* = 2)
Angles	EPA	IPA	Ridge angle	-	-	Angles	EPA	IPA	Ridge angle	-	-	-
	82°	112°	62.7°	-	-		83.1°	105.6°	67.7°	-	-	-
Cross section	Obtuse triangle	Isosceles trapezoid	Parallelogram	Undeter.	-	Cross section	Obtuse triangle	Isosceles trapezoid	Parallelogram	Undeter.	Right triangle	-
	72.7% (*n* = 8)	9% (*n* = 1)	9% (*n* = 1)	9% (*n* = 1)	-		60% (*n* = 12)	-	20% (*n* = 4)	15% (*n* = 3)	5% (*n* = 1)	-
End termination	Feather	Overshot	Hinge	Broken\undeter.	-	End termination	Feather	Overshot	Hinge	Broken\undeter.	-	-
	-	45% (*n* = 5)	36% (*n* = 4)	18% (*n* = 2)	-		15% (*n* = 3)	10% (*n* = 2)	50% (*n* = 10)	25% (*n* = 5)	-	-
Prepared core CTEs (n = 10)	-	-	-	-	-	*Prepared core CTEs (n = 40)*	-	-	-	-	-	-
Scar pattern on the dorsal face	Centri.	Unidir.	Bidi.	-	-	Scar pattern on the dorsal face	Centri.	Unidir.	Bidi.	-	-	-
	70% (*n* = 7)	20% (*n* = 2)	10% (*n* = 1)	-	-		72.4% (*n* = 29)	22.5% (*n* = 9)	2.5% (*n* = 1)	-	-	-
Scars number (av.)	6	-	-	-	-	Scars number (av.)	5.6	-	-	-	-	-
Striking platform preparation	Plain	Punctiform	Faceted	Undeter.	Dihedral	Striking platform preparation	Plain	Punctiform	Faceted	Undeter.	Dihedral	Linear
	40% (*n* = 4)	-	20% (*n* = 2)	30% (*n* = 3)	10% (*n* = 1)		12.5% (*n* = 5)	5% (*n* = 2)	22.5% (*n* = 9)	-	2.5% (*n* = 1)	2.5% (*n* = 1)
Angles	EPA	IPA	Ridge angle	-	-	Angles	EPA	IPA	Ridge angle	-	-	-
	73°	111°	70°	-	-		78.7°	110.1°	66.1°	-	-	-

(Continued on following page)

TABLE 5 | (*Continued*) Major attributes of the two CTE types from both sites. Prefer. (Preferential); Rec. (Recurrent); centri. (centripetal); uni. (unidirectional); bidi. (bidirectional); Undeter. (Undetermined).

CTE	Revadim (*n* = 21)						Jaljulia (*n* = 60)					
Cross section	Obtuse triangle	Isosceles trapezoid	Parallelogram	Undeter.	Equilateral triangle	Cross section	Obtuse triangle	Isosceles trapezoid	Parallelogram	Undeter.	Equilateral triangle	Right triangle
	60% (*n* = 6)	10% (*n* = 1)	10% (*n* = 1)	10% (*n* = 1)	10% (*n* = 1)		62.5% (*n* = 25)	-	20% (*n* = 8)	10% (*n* = 4)	2.5% (*n* = 1)	5% (*n* = 2)
End termination	feather	overshot	hinge	broken\undetermined	-	End termination	feather	overshot	hinge	broken\undetermined	retouched	-
	40% (*n* = 4)	30% (*n* = 3)	-	30% (*n* = 3)	-		22.5% (*n* = 9)	15% (*n* = 6)	30% (*n* = 12)	15% (*n* = 6)	17.5% (*n* = 7)	-

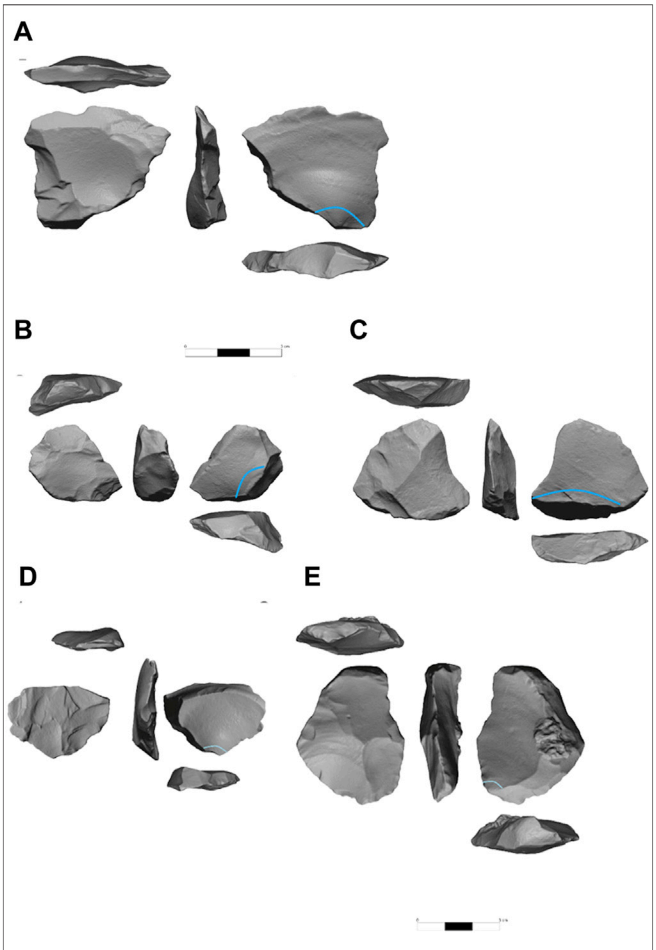

FIGURE 8 | *Éclats débordants* CTEs from Jaljulia. The bulb of percussion is highlighted by a blue line. **(A–D)** *Éclats débordants*; **(E)** *Outrepassé*. Note that for this item, not only has the lateral ridge of the core been removed but the distal one as well.

chunks. This flexibility on the part of the knappers further highlights the importance of this technological trajectory and the level of knowhow and intentionality practiced by early humans during late Acheulian times in the Levant. We wish to emphasize that systematic lithic recycling in the late Lower Paleolithic has been demonstrated time and again for the production of small sharp flakes from "parent" flakes (Barkai et al., 2010; Agam et al., 2015; Lemorini et al., 2015; Parush et al., 2015; Agam and Barkai, 2018a; Venditti et al., 2019a; Venditti et al., 2019b), as well as the transformation of handaxes into cores (DeBono and Goren-Inbar, 2001; Marder et al., 2006; Shimelmitz, 2015; Akhilesh et al., 2018; Rosenberg-Yefet and Barkavi, 2019), and the use of old patinated flaked items for the production of new items such as cores and tools (Vaquero et al., 2015; Lemorini et al., 2016; Agam and Barkai, 2018a; Efrati et al., 2019). The evidence presented here thus adds to our growing knowledge regarding the role of lithic recycling in late Lower Paleolithic assemblages while also emphasizing inter site variability, as the Jaljulia prepared cores were not part of this intriguing behavioral pattern.

3.2 Characteristics of the Two Types of Core Trimming Elements From Both Sites

The major attributes and metrics of the CTE assemblages from Revadim and Jaljulia are presented in **Table 5** and **Supplementary Table S5**.

Éclats débordants (Revadim: *n* = 11; Jaljulia: *n* = 20): This group was further divided into *éclats débordants* (**Figures 8A–D**; **Figures 9A,B**), *éclats débordants a dos limité* (**Figure 9D**), and *outrepassé*s (**Figure 8E**; **Figure 9C**). Due to the small sample size of each group, the analysis below will be presented for all sub-types together. Most items are characterized by a centripetal scar pattern on the dorsal face while the minority are unidirectional or bidirectional, with an average of seven scars on the dorsal face for Revadim and 5.3 for Jaljulia. The items have quite similar average EPA (Revadim: 82°; Jaljulia: 83.1°), reflecting the angle between the two platforms of the core from which they were removed, and an average IPA of 112° for Revadim and 105.6° for Jaljulia, indicating the angle of removal of the items. Variability in striking platform preparation was also noted, as some are plain, punctiform, faceted, dihedral, linear, or undetermined. At Revadim, only one item was removed from the right lateral part of the core, while the rest were removed from the left lateral part of the core (**Figure 10A**). At Jaljulia, most items were removed from the right lateral part of the core, while only a few were removed from the left lateral part of the core (**Figure 10B**). The average angle of the ridge removed from the core is quite similar for both sites (Revadim: 62.7°; Jaljulia: 67.7°). The EPA and ridge angle both mirror the original core circumference at different locations on the core. The difference between the EPA and the ridge angle is relatively large (about 20°), which might indicate a calculated decision on the part of the knapper as to where to strike the blow, even for centripetal cores that seem at first glance to be rounded and symmetrical. The cross sections of most items are obtuse triangles, while the rest are isosceles trapezoids, right triangles, parallelograms, or undetermined. The end terminations of the items vary between overshot (**Figure 8E**; **Figure 9C**), feather (**Figures 8A,C**; **Figure 9A**), hinge (**Figures 8B,D**), and broken\undetermined. (See **Figure 9D**).

Prepared core CTEs (Revadim: *n* = 10; Jaljulia: *n* = 40): Most items bear a centripetal scar pattern on the dorsal face while the minority are unidirectional or bidirectional, with an average of six scars on the dorsal face for Revadim and 5.6 for Jaljulia. The items have quite similar average EPA (Revadim: 73°; Jaljulia: 78.7°), reflecting the angle between the two platforms of the core from which they were removed, and an average IPA of 111° for Revadim and 110.1° for Jaljulia, indicating the angle of removal of the items. Variability in striking platform preparation was also noted, as some are plain, punctiform, faceted, dihedral, linear (or undetermined. At Revadim, half of the items were removed from the left lateral part of the core and 40% (*n* = 4) from the right lateral part of the core (**Figure 10A**); the remaining 10% were removed from the proximal end. Similarly, at Jaljulia, about half of the items were removed from the left lateral part of the core, and the other half from the right lateral part of the core (**Figure 10B**); the remaining 5% were removed from the proximal end. The average angle of the ridge removed from the core is quite similar for both sites (Revadim: 70°; Jaljulia: 66.1°). Here, too, the large difference between the EPA and the ridge angle might indicate a deliberate decision as to where to strike the core, as explained above. Most items have an obtuse triangular cross section, while the rest consist of a few different cross section types (**Table 5**). The end terminations of the items vary, but the most common are overshot, and hinge (**Table 5**).

3.3 Characteristics of Blanks Produced From Prepared Cores, From the Two Sites

The frequency of blanks produced from prepared cores differs significantly for the two sites (Jaljulia, *n* = 99; Revadim, *n* = 8). Since the number of items from Revadim is very small, quantitative analysis is not possible and thus the data will be presented separately for each site.

3.3.1 Revadim Blanks Produced from Prepared Cores (*n* = 8), (Figure 11)

The majority of items exhibit a centripetal dorsal scar pattern (*n* = 6) while two of the items exhibit a unidirectional scar pattern, all having 7–8 scars on the dorsal face. The flakes have plain (*n* = 5), faceted (*n* = 2) or dihedral (*n* = 1) striking platforms with an average IPA of ca. 110° and EPA of ca. 83.7°. Flake terminations are feather (*n* = 3), overshot (*n* = 1), hinge (*n* = 1), retouch (*n* = 1), or undetermined (*n* = 2). Flakes are 4 cm long, 3.2 cm wide, and 0.5 cm thick on average.

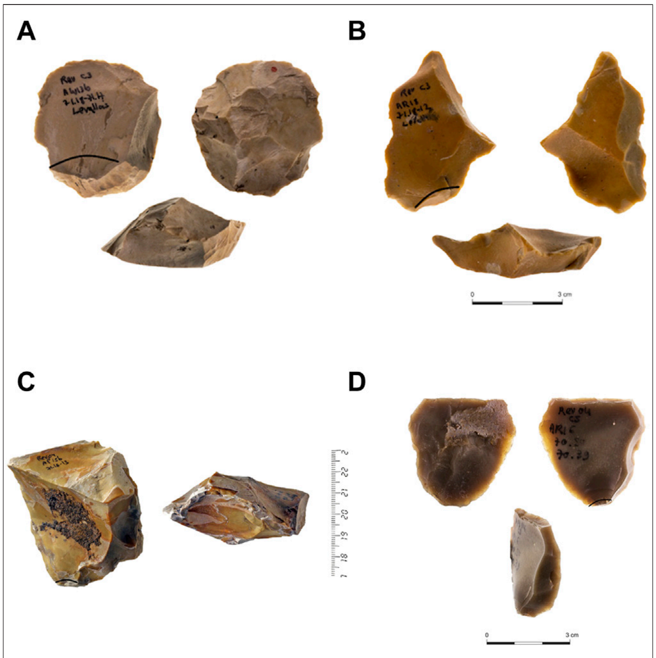

FIGURE 9 | (A,B) *Éclats débordants* CTEs from Revadim. **(C)** *Outrepassé* CTE from Revadim. Note that this item may have been removed from the core in order to overcome obstacles in the flint; **(D)** *Éclats débordants a dos limité*. The bulb of percussion is highlighted by a black line.

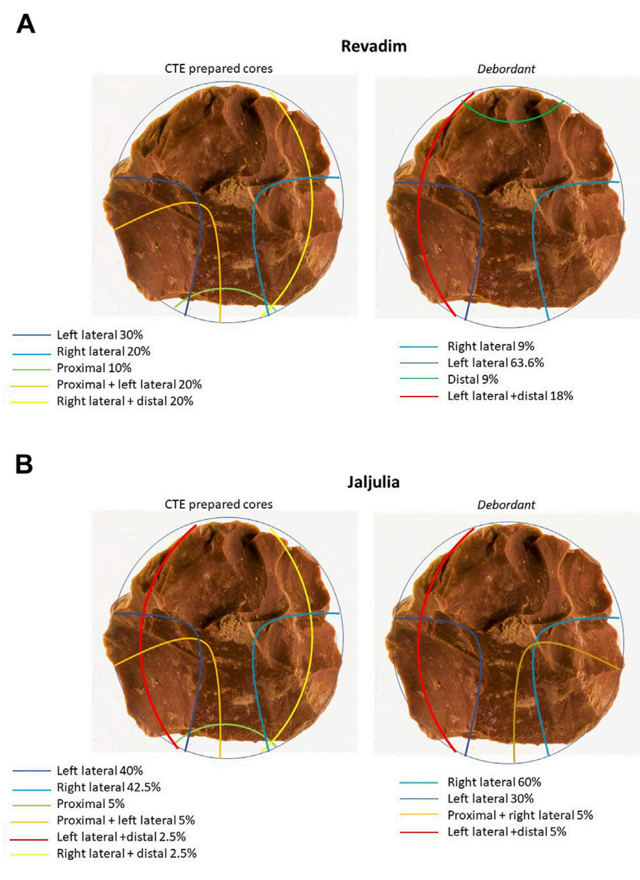

FIGURE 10 | Prepared core CTEs and *débordant* items from Revadim **(A)** and Jaljulia **(B)**, showing the location of removal in relation to the core circumference. Note that the core is shown for illustrative purposes only.

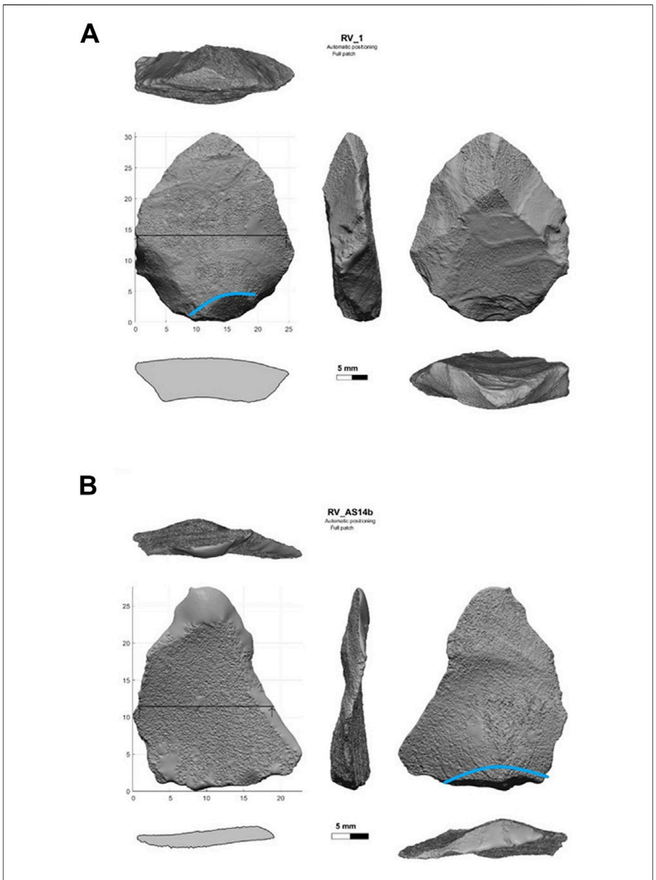

FIGURE 11 | (A,B) Prepared cores flakes from Revadim. The bulb of percussion is highlighted by a blue line. Jaljulia blanks produced from prepared cores (*n* = 99).

3.3.2 Jaljulia Blanks Produced from Prepared Cores (*n* = 99)

The major attributes and metrics of blanks produced from prepared cores from Jaljulia are presented in **Table 6**, **Supplementary Table S6**, and **Figure 12**.

Items usually exhibit a centripetal dorsal scar pattern (62.6%, *n* = 62) or otherwise unidirectional (31.3%, *n* = 31), with an average of 6.1 scars on the dorsal face. Flakes are characterized by an IPA of ca. 112.3°. Most flakes have a faceted striking platform, while the rest are plain, dihedral or less frequently represented, and their average EPA is ca. 79.3°. The end terminations of the items vary between feather, hinge, retouched, and undetermined. Half of the flakes are uniform in thickness, while 40% are irregular. Of those, all are thicker at the base and thinner at the distal end. The rest of the flakes are moderately uniform or broken.

4 DISCUSSION

4.1 Comparative Analysis of the Revadim and Jaljulia Samples

We analyzed the techno-typological characteristics of prepared cores and blanks originating from four layers of Revadim and one excavation area from Jaljulia, including all observable aspects of the core reduction sequence. Three sub-types of prepared cores were defined at Revadim and Jaljulia: prepared cores (general), discoid cores, and proto-Levallois cores. Proto-Levallois and prepared cores (general) adhere to concepts characteristic of the Levallois method. We thus believe that the production of predetermined blanks in the late Acheulian should be viewed as a precursor of the fully-fledged Levallois method of the Middle Paleolithic Mousterian.

Proto-Levallois and Mousterian Levallois cores bear many similarities, the most important of which is the shaping into two hierarchical surfaces. Additionally, both relied on the preparation of core convexities to produce predetermined blanks, on the creation of a ridge intersecting the two core surfaces acting as a striking platform, and on the removal of predetermined blanks in parallel with the plane of intersection. Moreover, in both cases, the cores were maintained by systematically removing *éclats dèbordants* flakes in order to control core convexities. This evidence suggests that the conceptualization of predetermined blank production—what has come to be known as the Levallois reduction concept—first emerged during late Acheulian times in the Levant.

Discoid cores are considered here as part of the parcel of prepared core technologies and are mostly characterized by a lack

TABLE 6 | Major attributes of blanks produced from prepared cores, from Jaljulia. Prefer. (Preferential); Rec. (Recurrent); Centri. (centripetal); Uni. (unidirectional); Bidi. (bidirectional); Undeter. (Undetermined); En chapeau. (*En chapeau de gendarme*).

	Jaljulia						
Blanks produced from prepared cores (*n* = 99)							
Scar pattern (dorsal face)	Centri.	Uni.	Bidi.	Undeter.	-	-	-
	62.6% (*n* = 62)	31.3% (*n* = 31)	4% (*n* = 4)	2% (*n* = 2)-	-	-	-
Average number of scars	6.1	-	-	-	-	-	-
	-	-	-	-	-	-	-
Striking platform preparation	Plain	Punctiform	Faceted	Undeter.	Dihedral	*En chapeau.*	Cortical
	11.1% (*n* = 11)	2% (*n* = 2)	60% (*n* = 60)	4% (*n* = 4)	17% (*n* = 17)	3% (*n* = 3)	2% (*n* = 2)
Angles	EPA	IPA	-	-	-	-	-
	79.3°	112.3°	-	-	-	-	-
End terminations	Feather	Overshot	Hinge	Undeter.	Retouched	-	-
	46% (*n* = 46)	3% (*n* = 3)	26% (*n* = 26)	15% (*n* = 15)	9% (*n* = 9)	-	-

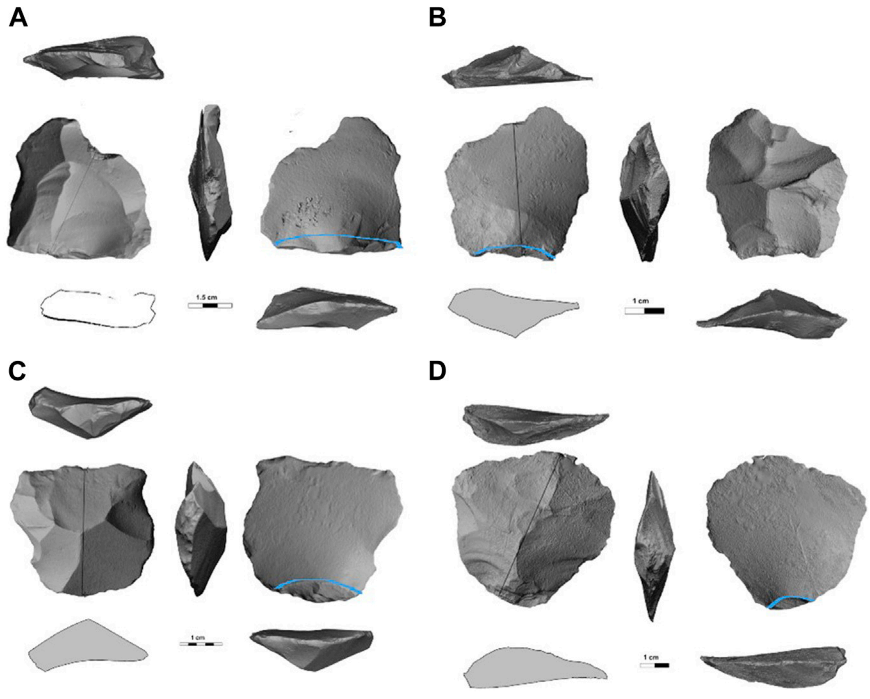

FIGURE 12 | (A–D) Blanks produced from prepared cores, from Jaljulia. The bulb of percussion is highlighted by a blue line.

of hierarchy between core platforms (or having a switchable hierarchy), and by the removals of flakes at a typical obtuse angle. The discoid cores represented here differ somewhat from the classic Middle Paleolithic discoid cores, as a significant number of the scars cross the core midline, a feature not typical of later discoid cores. Prepared core CTEs, not commonly represented in Lower Paleolithic sites in the Levant, further add to our understanding of the complete reduction sequence. Prepared cores (general) reflect, in our view, a less distinctive technological procedure than the proto-Levallois and discoid. The technological analysis presented above suggests that this reduction sequence is predetermined, albeit less systematically, than the other two methods. A thin line separates this group of cores from the proto-Levallois ones. It is possible that cores defined by us as prepared cores (general) actually represent less successful attempts to execute the proto-Levallois method. Moreover, many of the CTEs defined by us as prepared core CTEs resemble *débordant* items, and were not classified as such only because they do not precisely fit the definition. With regard to the previously discussed difficulty of correctly identifying a variant that is on the periphery of a particular technology, the definition of this group as distinct from the proto-Levallois and discoid cores is intended as a possible methodological solution for such cases. We thus argue that proto-Levallois and prepared cores (general) should be viewed as a technological and conceptual continuum, reflecting early stages of the assimilation and adoption of predetermined blank production in the late Lower Paleolithic Levant.

The Revadim and Jaljulia cores were meticulously designed by both preparation removals and *débordant* removals, intended to facilitate the later production of desired predetermined items. The proto-Levallois reduction sequence is generally similar at both sites, excluding some differences that will be mentioned below. Notably, the proto-Levallois reduction sequence we defined here has been documented in other late Acheulian sites in the Levant and beyond (Gilead and Ronen, 1977; Goren, 1979; Ronen et al., 1980; Goren-Inbar, 1985; Chazan, 2000; DeBono and Goren- Inbar, 2001; Goren-Inbar, 2011; Shimelmitz et al., 2016; Zaidner and Weinstein-Evron, 2016; Goren-Inbar et al., 2018), and it thus can be seen as a hallmark of the late Acheulian lithic repertoire. In this paper we present the first comprehensive and detailed analysis of this intriguing phenomenon.

Although prepared cores and blanks represent a small percentage of the core and blank assemblages at both sites (Revadim: Agam et al., 2015; Solodenko 2010; Rosenberg-Yefet and Barkai 2019), we believe that their ubiquitous presence in every lithic assemblage at these two late Acheulian sites reflects the habitual use of prepared core technologies during this period in the Levant.

Proto-Levallois cores were more intensively shaped than discoid and prepared cores (general), as can be construed from the number of scars, scars representing *débordant* items, and cortex coverage. Discoid cores, however, were more systematically shaped around the circumference of the cores than the proto-Levallois cores, a difference that might be explained by their having been reduced along the entire core circumference, whereas reduction in proto-Levallois cores tended to be more restricted. The larger number of *éclats débordants* removals observed on the proto-Levallois cores might also explain this difference, as they might have spared the knapper the need to shape the entire circumference by means of bifacial flaking. Shaping the convexities of proto-Levallois cores by *éclats débordants* removals requires fewer bifacial blows at the lateral edges of the cores, as is common in Mousterian assemblages as well (Beyries and Boëda, 1983; Geneste, 1985:230; Meignen, 1995:280; Hovers, 2009:82; Shimelmitz and Kuhn, 2013; Hu et al., 2019). The use of *débordant* removals in order to design and maintain prepared cores in late Acheulian assemblages requires both expertise and an understanding of the blow direction, angle of striking, and precise use of force. The appearance of this technique as early as the late Acheulian demonstrates that knappers had the cognitive capabilities to master this distinctive and complex maintenance procedure long before its widespread adoption during Middle Paleolithic times.

The CTEs, included as part of our analysis of the entire reduction sequence and all its components, provide a glimpse into the initial shaping and maintenance stages of prepared cores: pre-planned core design and the strict adherence to concepts related to core volume and convexities. The presence of *éclats débordants* clearly demonstrates similarities in core design and maintenance with the fully-fledged Middle Paleolithic Levallois method, while *éclats débordants a dos limité* can be assigned, in the assemblages analyzed in this paper, to either the Levallois or the discoid methods.

Given the data presented above, the entire reduction sequence of prepared cores appears to be better represented in the Jaljulia sample than in the Revadim sample. This is reflected in the more frequent occurrence of both CTEs and blanks related to these core methods. Nevertheless, we have little doubt that the CTE items associated with prepared cores at Revadim also attest to the execution of core preparation and maintenance related to the Levallois concept. The high frequency of items characterized as *éclats débordants* in layer C3 East at Revadim, an assemblage analyzed by Malinsky-Buller et al. (2011), is noteworthy in this regard. The assemblage includes 209 *éclats débordants* and 56 *outrepassés*. Prepared cores (n = 61), or, in the authors' terminology—cores with two surfaces perpendicular to each other with hierarchy—comprise 13% of all the cores in area C East. Intra-site variability in the application and intensity of prepared core technologies is of course to be expected, but nor can one disregard the presence of prepared core technologies at every single archaeological context at Revadim. We hope to gain a clearer understanding of intra-site variability once detailed analysis of all the areas at Jaljulia is complete.

The ridge angles of the *éclats débordants* items (Revadim: 62°; Jaljulia: 67°) differ significantly from the EPA angles (Revadim: 82°; Jaljulia: 83°). These angular differences reflect the asymmetry in the two platforms along the core circumference, a feature that generally characterizes proto-Levallois rather than discoid cores. *Éclats débordants* might thus have been detached mostly from the former type.

Inter-site variability can also be observed in the striking platforms of the *éclats débordants* items from the two sites. Whereas the Jaljulia items frequently exhibit faceted and dihedral striking platforms (*éclats débordants*: faceted, 45%; dihedral, 15%), these features are less frequent at Revadim (*eclats débordants*: faceted, 18%; dihedral, none). Even fewer of these faceted striking platforms (14.5%) were observed for the *éclats débordants items* in layer C3 East (Malinsky-Buller et al., 2011). In Mousterian sites, faceted or dihedral striking platforms are usually better represented (for example at Tabun; see Shimelmitz and Kuhn, 2013). The greater number of faceted striking platforms at Jaljulia is correlated with the more intensive treatment of convexities along the proto-Levallois core circumference (**Tables 1**, **4**). The larger number of CTE items as well as the more intensive shaping of their striking platforms at Jaljulia might indicate greater assimilation of the Levallois concept there than at Revadim. The removal of these items was not symmetrical, as *éclats débordants* were repeatedly struck from one edge of the core: 81.6% were removed from the left lateral side at Revadim (**Figure 10A**) and 65% from the right lateral side at Jaljulia (**Figure 10B**). This asymmetrical treatment of core convexities is also common in other Middle Paleolithic Levallois assemblages in the Levant (Shimelmitz and Kuhn, 2013) and might reflect some technological continuity between late Acheulian proto-Levallois to the Middle Paleolithic Levallois.

As for blanks produced from prepared cores, the small number of these items at Revadim precludes a comparison between the two sites. Their infrequency is perhaps due simply to the difficulty in identifying these items. In this study, no distinction was made between proto Levallois flakes, discoid flakes and prepared cores (general) flakes. We are currently developing the methodology required to distinguish between these categories, to be published in future study. In a recent paper, González-Molina et al. (2020) used machine learning algorithms to address the challenges of distinguishing between discoid and Levallois flakes. Width at 50 and 75% of the flake length, inner angle, and maximum width were found to be the best parameters for accurate classification. The large number of faceted platforms in the Jaljulia assemblage is documented in many other Levallois assemblages, for example, at the Early Middle Paleolithic site of Misliya Cave, where convex faceted and “chapeau de gendarme” striking platforms are seen as diagnostic features of the Levallois method (Zaidner and Weinstein-Evron, 2020). These along with other factors will be considered in the future.

4.2 Environmental Considerations

Changes in the Levantine habitat towards the end of the Lower Paleolithic might have played a role in the invention, adoption and assimilation of the Levallois method. The disappearance of elephants from the Levantine post-Acheulian landscape, marking the end of the Acheulian mode of adaptation, was probably a slow process, but one that must have had severe consequences for the Acheulian groups, who had lived in their presence for hundreds of thousands of years. The strong spiritual bond between early humans and elephants might be expressed in the production of replicas of the iconic handaxes from elephant bones, which seems to have accelerated towards the end of the Acheulian (Mussi, 2005; Costa, 2010; Zutovski and Barkai, 2016; Barkai, 2019; Barkai, 2021).

We suggest grouping together these separate lines of evidence into what seems to all be part of the same story: the assimilation and adoption of the Levallois method has its roots in the late Lower Paleolithic and might also have been driven by the disappearance of elephants from the Levantine habitat. This major habitat change may have created a “cultural storm” in which the adoption and assimilation of the Levallois method began in the late Acheulian, before the final extinction of the elephants, and became much more pronounced during the Middle Paleolithic. The AYCC, with its transition to the hunting and consumption of smaller prey, demonstrated a different kind of human adaptation and might well be part of the same story (e.g. Barkai et al., 2017).

4.3 The Adoption and Assimilation of Technological Innovations During Lower Paleolithic Times

The study of prepared core technologies at Revadim and Jaljulia provides an interesting observation point regarding the adoption and assimilation of technological innovations during Lower Paleolithic times. Technological innovations often involve a long and multi-participant process as the idea progresses and develops in what is known as “cumulative culture” (Tomasello, 1999; Hoppitt and Laland, 2013), also sometimes termed the ratchet effect (Tomasello, 1999; Tennie et al., 2009; Mesoudi, 2011). It has been argued that this accumulation of knowledge requires high-fidelity social learning mechanisms in order to allow the transmission of innovative ideas (Boyd and Richerson, 1988; Acerbi and Mesoudi, 2015; Tennie et al., 2016; Tennie et al., 2017). Some of us have previously argued that evidence for the existence of cumulative culture appears as early as the end of the Lower Paleolithic (Rosenberg-Yefet et al., 2021).

When considering the life cycle of a technological innovation, a few steps are generally expected: a slow inception, gradual assimilation of the technology, an increase in its frequency up to a certain peak, and then a decline, in an S curve representation, created by differences among individuals in their degree of “innovativeness” (although not all adoption curves are S-shaped) (Henrich, 2001). Five adopter categories are usually considered: innovators, early adopters, early majority, later majority, and laggards (Valente, 1996; Henrich, 2001). These differences between early and late adopters can create inter-individual variability regarding some technologies (Roux et al., 2018). This variability is expressed both in inter-group variability between individuals (Rogers, 2003; Correa, 2016; Assaf, 2021; Gandon et al., 2021) and, if we view the bigger picture in lower resolution, in inter-site variability along the chrono-geographical range. Many factors determine how innovative ideas and technologies are disseminated, including scales of mobility, population size, connectivity and networks, population stability, the presence of “weak ties”, defined as occasionally accessed connections (as opposed to “strong ties” such as family/kin), and environmental richness (Kuhn, 2012; Collar et al., 2015).

Given these high-resolution and low-resolution views of technological variability, we can see why a technology might be expected to differ in its initial versus peak phases. These differences will be expressed in the level of standardization and in the distinctiveness of the technology. Hence, we expect that some traits of a technology will be less standardized during the initial phases of adoption.

The Revadim and Jaljulia proto-Levallois assemblages reflect, in our opinion, an initial phase of technological adoption and assimilation. The partial correspondence of the proto-Levallois cores, CTEs, and prepared core end products to the Mousterian Levallois definition reveals the conceptual principles that will later define the technology at its peak phase.

The percentage of prepared cores among the total number of cores at Acheulian sites varies but remains a noteworthy phenomenon. At Berekhat Ram, for example, 64.8% of the cores are prepared (sample size is, however, restricted) (Goren-Inbar, 1985). At Holon, while only 3.2% of the cores are prepared, this percentage increases to 19.3% for cores with hierarchy, which might correspond to our definition of prepared cores) (Malinsky-Buller, 2014). At the different layers of Gesher Benot Ya'aqov, 5.2–17.3% of the cores are prepared (Goren-Inbar et al., 2018). These are but a few of many examples of assemblages that might reflect early stages of adoption of the technology, as suggested for the Revadim and Jaljulia cases, and therefore can be seen as part of the chrono-geographical range of inter-site variability, mentioned earlier.

The early appearance of prepared cores at both sites signals, in our view, the inception of concepts related to the Levallois method, termed here proto-Levallois, in the late Acheulian Levant. The technological and conceptual characterization of the initial stage presented here reflect a broader behavioral model of adoption and assimilation of technological innovations during Lower Paleolithic times.

5 CONCLUSION

Scholars agree that the Levallois method reflects high technological proficiency, depth of planning, and structured cultural norms that were shared by Neanderthals, modern humans, and other human groups of the Middle Paleolithic period. In this study we showed that these capabilities were also within the reach of late Acheulian early humans, and that techniques for predetermined blank production, later to be associated with the Levallois, were invented, developed, and geographically dispersed during late Lower Paleolithic times in the Levant.

The prepared core assemblages from Revadim and Jaljulia reflect a significant step forward in terms of knapping organization, depth of planning, and successful predetermination of the items produced, considered by many to be unparalleled until the Middle Paleolithic, when the Levallois method took central stage. The Jaljulia area B assemblage represents a more advanced stage in the assimilation of the Levallois concept than the Revadim assemblage, as attested to by the cores, CTEs and blanks that we analyzed in our study, possible inter- and intra-site variability notwithstanding. Preliminary chronological data places area B at Jaljulia relatively late in the late Acheulian (Shemer et al., submitted) so chronology might also explain the more advanced implementation of predetermined production at this site. These assumptions will be further investigated in the future, as more absolute dates are determined for the two sites.

Our analysis of cores, CTEs, and end products quite clearly demonstrates that the early appearance of predetermined blank production via the Levallois method (referred to here as proto-Levallois) reflects a stage in the adoption, spread and assimilation of a new and significant technological innovation in the Old World, one that would be developed later into the Mousterian Levallois. The late Acheulian adoption of Levallois concepts is one of the most significant developments in the cultural evolution of Paleolithic knapping systems and, as such, a remarkable milestone in human cultural evolution.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

TR-Y analyzed all lithic material, organized and analyzed database and wrote the manuscript. RB participated in data analysis and manuscript writing. MS excavated the Jaljulia site and participated in manuscript writing. All authors contributed to manuscript revision, read, and approved the submitted version.

FUNDING

This work was supported by Israel Science Foundation grant 321/19 entitled “Late Acheulean Jaljulia—A lithic perspective” and by the joint UGC–ISF Research Grant (Israel-India program) entitled “The First Global Culture: Lower Paleolithic Acheulean Adaptations at the Two Ends of Asia” 2712/16.

ACKNOWLEDGMENTS

We would like to express gratitude to our editor, Sharon Kessler, for providing useful comments to improve the paper. We also wish to thank Sasha Flit (TAU) for the photographs used in this article and Leore Grosman and Gadi Herzlinger for the 3D scans. We would like to specially thank Liliane Meignen for her help in guiding us through the lithic analysis of the Levallois-related assemblages.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2022.847358/full#supplementary-material

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ORIGINAL RESEARCH
published: 21 April 2022
doi: 10.3389/fevo.2022.881651

Insights on the Early Pleistocene Hominin Population of the Guadix-Baza Depression (SE Spain) and a Review on the Ecology of the First Peopling of Europe

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OPEN ACCESS

Edited by:
Marta Arzarello, University of Ferrara, Italy

Reviewed by:
Juan Rofes, University of the Philippines Diliman, Philippines
Raymond Louis Bernor, Howard University, United States

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Specialty section:
This article was submitted to Paleontology, a section of the journal Frontiers in Ecology and Evolution

Received: *22 February 2022*
Accepted: *14 March 2022*
Published: *21 April 2022*

Citation:
Palmqvist P, Rodríguez-Gómez G, Bermúdez de Castro JM, García-Aguilar JM, Espigares MP, Figueirido B, Ros-Montoya S, Granados A, Serrano FJ, Martínez-Navarro B and Guerra-Merchán A (2022) Insights on the Early Pleistocene Hominin Population of the Guadix-Baza Depression (SE Spain) and a Review on the Ecology of the First Peopling of Europe. Front. Ecol. Evol. 10:881651. doi: 10.3389/fevo.2022.881651

The chronology and environmental context of the first hominin dispersal in Europe have been subject to debate and controversy. The oldest settlements in Eurasia (e.g., Dmanisi, ∼1.8 Ma) suggest a scenario in which the Caucasus and southern Asia were occupied ∼0.4 Ma before the first peopling of Europe. Barranco León (BL) and Fuente Nueva 3 (FN3), two Early Pleistocene archeological localities dated to ∼1.4 Ma in Orce (Guadix-Baza Depression, SE Spain), provide the oldest evidence of hominin presence in Western Europe. At these sites, huge assemblages of large mammals with evidence of butchery and marrow processing have been unearthed associated to abundant Oldowan tools and a deciduous tooth of *Homo* sp. in the case of BL. Here, we: (i) review the Early Pleistocene archeological sites of Europe; (ii) discuss on the subsistence strategies of these hominins, including new estimates of resource abundance for the populations of Atapuerca and Orce; (iii) use cartographic data of the sedimentary deposits for reconstructing the landscape habitable in Guadix-Baza; and (iv) calculate the size of the hominin population using an estimate of population density based on resource abundance. Our results indicate that Guadix-Baza could be home for a small hominin population of 350–280 individuals. This basin is surrounded by the highest mountainous reliefs of the Alpine-Betic orogen and shows a limited number of connecting corridors with the surrounding areas, which could have limited gene flow with other hominin populations. Isolation would eventually lead to bottlenecks, genetic drift and inbreeding depression, conditions documented in the wild dog population of the basin, which probably compromised the viability of the hominin population in the medium to long term. This explains the discontinuous nature of the archeological record in Guadix-Baza, a situation that can also be extrapolated to the scarcity of hominin settlements for these ancient chronologies in Europe.

Keywords: early *Homo*, Western Europe, subsistence strategies, Barranco León, Fuente Nueva 3, population size

INTRODUCTION

The chronology of the first hominin settlements in Europe has been subject to debate and controversy. Until the mid 1990s most paleoanthropologists believed that there was no significant habitation before 0.6–0.5 Ma (e.g., Aragó, Bilzingsleben, Boxgrove, Ceprano, Mauer, and Verteszöllos), with most sites concentrating on $\leq$0.45 Ma (e.g., Atapuerca's Sima de los Huesos, Petralona, Schöningen, Swanscombe, and Steinheim) (Carbonell and Rodríguez, 1994; Roebroeks and van Kolfschoten, 1994), an increase in the number of occupations that coincided with interglacial MIS 11 (Blain et al., 2021). This "young chronology" was shortly challenged by new findings in Europe (Carbonell et al., 1995; Ascenzi et al., 1996; Bermúdez de Castro et al., 1997; Martínez-Navarro et al., 1997), the Caucasus (Gabunia and Vekua, 1995) and China (Wanpo et al., 1995; Larick and Ciochon, 1996), as well as by the geochronological re-evaluation of the evidence from Java (Swisher et al., 1994; Larick et al., 2001; Hyodo et al., 2011), which all indicated an earlier hominin arrival in Eurasia, during late Early Pleistocene times (Arribas and Palmqvist, 1999). However, although the archeological record in Europe has improved over the last decades, it remains highly fragmentary for these ancient chronologies and many sites lack high-resolution chronostratigraphic frameworks, which raises doubts on the age of the earliest hominin settlements. For example, a re-evaluation of the magnetostratigraphic and radiometric age constraints on several key sites bearing hominin remains and/or lithic tools from southern Europe led Muttoni et al. (2010, 2013) to propose that the first hominin dispersal in Western Europe took place during the Matuyama reverse polarity chron, between the Jaramillo normal polarity subchron and the Brunhes-Matuyama boundary.

Ancient evidence of hominin presence in Western Europe, The Caucasus, the Levantine Corridor, and Northern Africa is now well documented in a number of Early Pleistocene archeological localities (see **Figure 1** and references therein). This provides a chronological scenario for the oldest hominin settlements in Eurasia in which the Caucasus (Dmanisi, ∼1.8 Ma) and southern Asia were occupied ∼400 ka before the first peopling of Europe (Arribas and Palmqvist, 1999; Dennell and Roebroeks, 2006; Mosquera et al., 2013). It has been proposed that this delay could result from competition with other carnivores: hominin survival at the middle latitudes, where plant resources are scarce during the cold season, would depend on the regular scavenging of ungulate carcasses (Turner, 1992; Palmqvist et al., 2022a). For this reason, Rodríguez-Gómez et al. (2017a) estimated the level of competition for meat among the members of the carnivore guild of Venta Micena (VM), a site dated by biochronology and paleomagnetism to 1.6–1.5 Ma with no conclusive evidence on hominin presence (Arribas and Palmqvist, 2002; Martínez-Navarro, 2002; Palmqvist et al., 2005). This study provided estimates on meat availability and competition intensity for VM that were higher and lower, respectively, than those obtained for Barranco León (BL) and Fuente Nueva 3 (FN3) (Rodríguez-Gómez et al., 2016a). Given that BL and FN3 are 200–100 ka younger than VM, this suggests that the delay in the colonization of Europe was not a matter of ecological opportunity and other factors (e.g., climatic and/or geographic barriers to dispersal) should be considered (Rodríguez-Gómez et al., 2017a).

The Early Pleistocene Archeological Sites of the Guadix-Baza Depression

Barranco León and FN3 lie in the NE sector of the Baza Basin (Guadix-Baza Depression, SE Spain; **Figure 2A**), in the vicinity of the town of Orce (**Figure 2B**). This sedimentary depression is an inland basin that covers an area of ∼4,000 km^2 and is surrounded by mountainous reliefs of the Betic Chains, with heights of up to 3,479 m in the Mulhacén peak. The continental Plio-Pleistocene record of the basin is composed of lacustrine and fluvial deposits that show a complex sedimentary architecture (both laterally and vertically) as a result from active tectonics and orbitally induced climatic cycles (García-Aguilar and Palmqvist, 2011). The sediments include limestones, marls, shales, sands, and conglomerates, as well as dark clays and silexites associated to the archeopaleontological sites (García-Aguilar et al., 2014, 2015). The basin was in connection with the Mediterranean Sea during Late Miocene times by the 'Almanzora Corridor' and became continental at the end of the Tortonian (Guerra-Merchán, 1990, 1993; Soria et al., 1999; but see also Husing et al. (2010)). Since these times, it was subject to isostatic uplift with an average uplift rate of ∼200 m/Ma, as estimated from Late Neogene coastal marine conglomerates and coral reefs (Braga et al., 2003). As a result, the glacis surface (i.e., the uppermost horizontal infilling level) stands now 1,000 m on average above sea level. During the Plio-Pleistocene, the basin developed a network of endorheic drainage, being subject to: (i) intense tectonic subsidence relative to the surrounding mountains, which facilitated the accumulation of a thick (∼550 m) and relatively continuous sedimentary record; and (ii) hydrothermal activity (**Figures 2A,B**), which provided a mild and productive environment for the terrestrial fauna (García-Aguilar et al., 2014, 2015). The thermal springs were a major determinant in the establishment of biodiversity 'hot spots' for the large mammal fauna, which remains were preserved in many sites like BL and FN3 (Palmqvist et al., 1996, 2005, 2022b; Arribas and Palmqvist, 1998; Viseras et al., 2006; Arribas et al., 2009; Maldonado-Garrido et al., 2017; Ros-Montoya et al., 2017; Martínez-Navarro et al., 2018).

The stratigraphy of BL (**Figure 2C**) spans the middle terrigenous and upper silty calcareous members of the Baza Formation (Vera et al., 1984). The middle member consists of alluvial red clays, sandstones and conglomerates while the upper one is dominated by limestones, sandstones, carbonate silts, and dark mudstones (Turq et al., 1996; Arribas and Palmqvist, 2002) deposited in a shallow lacustrine system with an alternation of oligo- to mesohaline waters (Anadón et al., 1994; Anadón and Gabàs, 2009). The excavated layers show sediments associated with a swampy environment, except level D (formerly BL5; Arribas and Palmqvist, 2002), which shows fluvial features and encases most of the archeological assemblage (Toro-Moyano et al., 2013). The sub-horizontal stratigraphy of FN3 (**Figure 2C**) shows two sedimentary cycles deposited in a lutitic-carbonate, lacustrine-to-swampy environment, each with limestones at the top of the sequence separated by clays, fine sands and marly lutites, which cluster in two main units, the Lower and Upper Archeological Levels (Turq et al., 1996; Martínez-Navarro et al., 1997; Espigares et al., 2013, 2019).

The age of BL-D (**Figures 2C,E**) and FN3 (**Figures 2C,D**) was estimated in 1.43 ± 0.38 and 1.19 ± 0.21 Ma, respectively, using biochronology, magnetostratigraphy and the U-series/electron spin resonance (ESR) dating method applied to optically bleached quartz grains and fossil teeth (Duval et al., 2012; Toro-Moyano et al., 2013). An age of 1.50 ± 0.31 Ma was derived for FN3 based on cosmogenic nuclides (Álvarez et al., 2015). Other age estimates were derived from a biometric approach that considered an orthogenetic, rectilinear pattern of size increase in the lower molar teeth of the arvicolid *Mimomys savini* (Lozano-Fernández et al., 2013, 2014), but this "vole-clock" was questioned (Martin, 2014; Palmqvist et al., 2014, 2016). The absence of suids from BL and FN3 provides also a useful biochronological inference (Martínez-Navarro et al., 2015): suids are absent from Europe between 1.8 and 1.2 Ma, until the arrival of an evolved form of *Sus strozzi* during the Epivillafranchian (Cherin et al., 2018, 2020). This species is first recorded in level TE9 (Atapuerca), dated at 1.22 ± 0.16 Ma by cosmogenic nuclides (Carbonell et al., 2008), and later in other sites of Jaramillo age like Untermassfeld, Vallonnet, or Vallparadís (Moullé et al., 2006; Madurell-Malapeira et al., 2010, 2014; Cherin et al., 2018, 2020).

Excavations through the last three decades in BL and FN3 have unearthed huge Oldowan assemblages composed of cores, flakes and debris that represent the whole reduction sequence (Tixier et al., 1995; Turq et al., 1996; Martínez-Navarro et al., 1997; Oms et al., 2000; Palmqvist et al., 2005; Barsky et al., 2010, 2016; Toro-Moyano et al., 2011, 2013; Espigares et al., 2013; Titton et al., 2018, 2021; Yravedra et al., 2021). The tools are associated to skeletal remains of vertebrates, mostly large mammals (>6,500 specimens in BL and >9,000 in FN3). Espigares et al. (2019) showed that of those bones with their cortical surface well preserved (4,249 in BL and 3,852 in FN3), 64 (0.8%) exhibited cut marks and 163 (2%) showed percussion marks resulting from bone fracturing by the hominins for accessing their marrow contents. Similarly, a recent study of 2,857 bone remains from FN3 unearthed during the excavation seasons of the years 2017–2020 has shown that 25 (0.9%) bear cut marks and 16 (0.6%), percussion marks (Yravedra et al., 2021). These frequencies are close to those recorded at Pirro Nord, where 1.1% of the remains are cut-marked and 0.6% show evidence of intentional bone breakage (Cheheb et al., 2019).

The anthropogenic marks of BL and FN3 provides clues on the subsistence strategies of the hominins that first dispersed in Europe (Espigares et al., 2013, 2019; Toro-Moyano et al., 2013; Yravedra et al., 2021). Cut marks are relatively short (length range: 1.8–13.0 mm) and are mostly represented by incisions, although scrapes, sawing marks, and chop marks are also documented. They mostly appear on remains of animals of medium-to-large and very large size, and evidence patterns of skinning, defleshing, disarticulation, evisceration, and periosteum removal. Percussion marks include pits, notches, impact flakes, and negative flake scars generated by hammerstone impact during the butchery of bones for marrow processing. There are also tooth-marked bones, most of them gnawed by the giant, short-faced hyena *Pachycrocuta brevirostris,* and some by porcupines (Espigares et al., 2019). This is particularly evident in the case of the Upper Archeological level of FN3, in which hyena coprolites are abundantly preserved (Espigares et al., 2013).

During the last years, a wealth of information on the taphonomy of the Orce sites, the technological features of their tool assemblages and the paleoecology of the faunal community has been published. This makes necessary a review of the paleoenvironments inhabited by the large mammals and the hominins in Guadix-Baza during late Early Pleistocene times, as a way of elucidating the ecological context in which the first hominin arrival in Western Europe took place. In this article, our three main goals are: (i) to review the subsistence strategies of the hominins in the archeological sites of BL and FN3; (ii) to evaluate the roles played by the hominins and carnivores in generating the fossil assemblages preserved at both sites; and (iii) to estimate the size of the hominin population that inhabited the basin.

MATERIALS AND METHODS

Our review of the evidence on hominin subsistence strategies includes: (i) the inferences on the mammalian fauna (**Table 1**) and the paleoenvironments of the basin; (ii) the technological features of the tool assemblages and the anthropogenic marks on the bones of large mammals; (iii) the scavenging opportunities provided by sabertooths to the hominins; and (iv) the inferences on the level of competition among the members of the carnivore guild and their consequences on hominin population density.

We use new data for evaluating the roles of hominins and carnivores as bone collecting and modifying agents in the assemblages of BL and FN3. Specifically, we study the abundance of proximal and distal epiphyses of major limb bones of ungulates and their relationship with the mineral density and marrow yields of these bone portions. For doing so, we use modern analogs (Outram and Rowley-Conwy, 1988; Brink, 1997; Lam et al., 1999) and least-squares regression techniques using SPSS Statistics v. 25. Then, we compare the results obtained with those for VM, a site conclusively identified as generated in the surroundings of a denning site of the large bone-destroying hyena *P. brevirostris* (Palmqvist et al., 1996, 2011, 2022b; Arribas and Palmqvist, 1998; Palmqvist and Arribas, 2001). Thirdly, we analyze with SPSS Statistics v. 25 the relationship between prey biomass availability and rainfall in a set of African Natural Parks and Game Reserves using data from Hatton et al. (2015) and Fick and Hijmans (2017). Then, we compare these results with the estimates available for BL and FN3 (Rodríguez-Gómez et al., 2016a, 2017a; Martín-González et al., 2019), to evaluate meat availability in the Orce sites. Finally, we develop a new model of the paleogeography of the Guadix-Baza Depression during the late Early Pleistocene using compiled data on the cartography on the sediments (García-Aguilar et al., 2014). This allows us to estimate with ImageJ v. 1.51 the extent of the paleoenvironments, which provides a reconstruction of the surface area habitable by the large mammals and the hominins. The cartographic surface, which encompasses the area covered by the lake, the outcrop

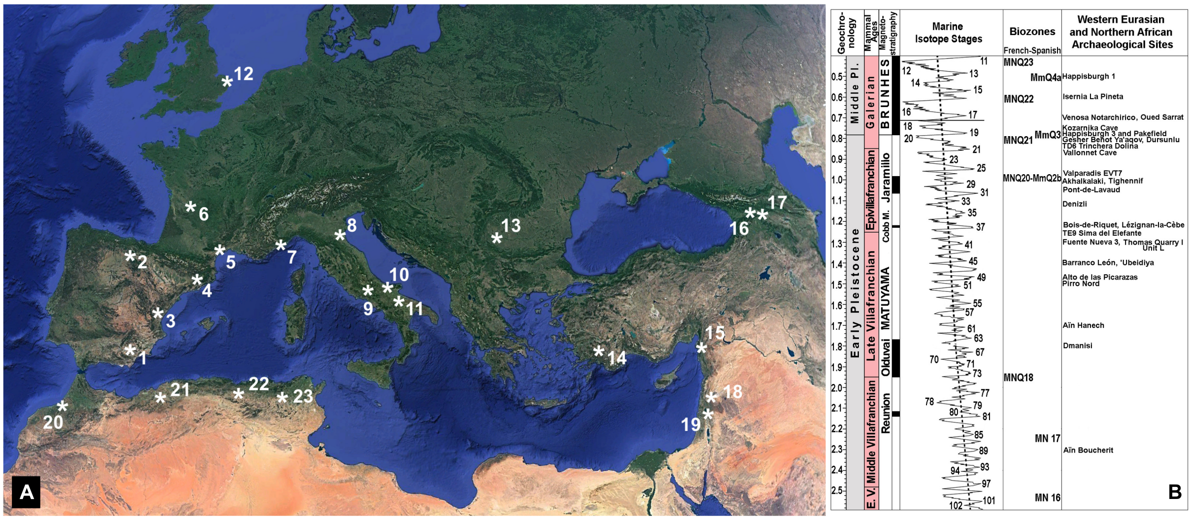

FIGURE 1 | (A) Geographic location of selected Early Pleistocene to early Middle Pleistocene archeological sites of Europe, North Africa, the Levantine Corridor, and the Caucasus. 1: Barranco León (BL) and Fuente Nueva 3 (FN3), two sites of the Guadix-Baza Depression, Spain (1.5–1.2 Ma; Martínez-Navarro et al., 1997; Oms et al., 2000; Espigares et al., 2013, 2019; Toro-Moyano et al., 2013; Titton et al., 2021; Yravedra et al., 2021), which have yielded abundant Oldowan assemblages (∼3,500 artifacts) and evidence of butchery and marrow processing of large mammal bones, as well as a human deciduous tooth in BL. 2: level TE9 of Sima del Elefante (1.3–1.1 Ma; Carbonell et al., 2008) and level TD6 of Trinchera Dolina (∼0.85 Ma, MIS 21; Duval et al., 2018; Parés et al., 2018) in Atapuerca, Spain (a mandibular symphysis and 32 Oldowan artifacts, including four flakes, used for defleshing and marrow extraction have been unearthed in TE9). 3: Alto de las Picarazas, Spain (1.5–1.4 Ma; Vicente-Gabarda et al., 2016), which preserves >2,000 bone remains (several of them with butchery, percussion, and fracture marks) and seven lithic tools (two shapeless flint fragments and some splinters found during the sieving of sediments). 4: Vallparadís, Level EVT7, Spain (0.98–0.95 Ma, MIS 27; Martínez et al., 2015; but see, for a younger chronology of ∼0.85 Ma, Duval et al., 2015), which has yielded small-sized Oldowan tools (notches, becs, scrapers and denticulates on small pebbles, clasts, fragments, and flakes, as well as a large single chopper) elaborated from local raw materials and based on an anvil knapping technique (Garcia et al., 2013). 5: Bois-de-Riquet, Lézignan-la-Cèbe (1.3–1.1 Ma; Bourguignon et al., 2016; but see, for an older chronology, Crochet et al., 2009), which preserves lithic artifacts (177 basalt tools, although anthropically produced artifacts are difficult to differentiate from fragments or blocks detached naturally from the exfoliating surfaces enclosing the sedimentary level). 6: Pont-de-Lavaud (1.1–1.0 Ma; Voinchet et al., 2010), with an Oldowan assemblage that comprises ∼8,000 artifacts made exclusively on quartz pebbles and subangular vein quartz fragments, including ∼4,000 broken pebbles and 1,321 pieces with percussion marks and evidence of flaking with the bipolar-on-anvil technique (De Lombera-Hermida et al., 2016). 7: Vallonnet Cave (1.2–1.1 Ma; Michel et al., 2017; Cauche, 2022), with percussion tools, shaped pebbles, flakes, cores, and cut-marked bones. 8: Monte Poggiolo, Italy (∼0.85 Ma, within the reverse magnetic polarity subchron C1r.1r; Muttoni et al., 2011), which preserves an industry characterized by knapped pebbles and the products derived from their knapping, showing an almost total absence of retouched tools and the presence of some scrapers and denticulates that seem to be incidental and have no distinctive features (Peretto, 2006). 9: Isernia La Pineta, Italy (∼0.6 Ma; Coltorti et al., 2005), with flint and cherty limestone artifacts associated with remains of large mammals, characterized by the use of anvils in an opportunistic and rapid way to produce a large number of flakes and residual cores, usually of very small size. 10: Pirro Nord, Italy (1.6–1.3 Ma; Arzarello et al., 2007, 2015; Cheheb et al., 2019), where 5 out of 340 lithic artifacts preserve use-wear traces and are associated with more than one thousand vertebrate fossil remains, several with cut marks or evidence of intentional breakage. 11: Venosa Notarchirico, Italy (0.695–0.670 Ma, MIS 17; Moncel et al., 2020), which Oldowan industry is made on chert and includes flakes (mostly unretouched), broken flakes, debris, retouched nodules, cores, and limestone pebbles, as well as two bifacial tools and a handaxe. 12: Happisburgh 3 and Pakefield, United Kingdom (∼0.8 Ma; Lewis et al., 2019), which tool assemblages comprise flint flakes, flake tools, cores, and a handaxe in the case of Happisburgh 1 (∼0.5 Ma, MIS 13). 13: Kozarnika Cave, Bulgaria, Layers 13a-c, Bulgaria (∼0.75 Ma; Muttoni et al., 2017), which has provided an abundant industry (∼10,000 artifacts, associated to a rich faunal assemblage) that shows a predominance of fragments from primary flaking (the local flint is very fragile), with the flakes obtained by simple unipolar to bipolar debitage (Sirakov et al., 2010). 14: Denizli, Turquey (1.2–1.1 Ma; Lebatard et al., 2014), which has provided the Kocabaş skull fragment, the only known Turkish fossil of *Homo erectus.* 15: Dursunlu, Turquey (0.99–0.78 Ma; Güleç et al., 2009), where remains of rhino, hippo and horse are found with 135 modified quartz implements. 16: Dmanisi, Georgia (∼1.8 Ma; García et al., 2010; Coil et al., 2020), a site that preserves the oldest evidence of human presence out of Africa (see text), with five hominin skulls and several postcranial bones (Gabunia and Vekua, 1995; Lordkipanidze et al., 2005, 2013), a rich assemblage of Late Villafranchian mammals and large numbers of Oldowan artifacts made of basalt, andesite and tuffs; the tool assemblage includes cores (mostly unifacial), flakes and debris, which shows that all stages of flaking activity took place

(Continued)

FIGURE 1 | at the site (Mgeladze et al., 2011). 17: Akhalkalaki, Georgia (1.0–0.9 Ma; Vekua, 1986), with thousands of remains of large mammals, including the giant hippo *H. antiquus* (not present in Dmanisi), and artifacts associated to the fauna, which could be not contemporaneous with it (Tappen et al., 2002). 18: Gesher Benot Ya'aqov, Israel (~0.78 Ma, MIS 19; Goren-Inbar et al., 2000), with an Acheulian assemblage composed of bifaces predominantly formed on basalt and core tools mostly made of flint. 19: 'Ubeidiya, Israel (~1.4 Ma; Martínez-Navarro et al., 2009, 2012), with rich core-choppers-flake assemblages and also a small but distinctive group of crude Early Acheulian bifaces, trihedrals, and quadrihedrals. 20: Thomas Quarry I-Unit L at Casablanca, Morocco (1.3–0.5 Ma; Gallotti et al., 2021), which preserves Acheulian assemblages made of quartzite and flint resulting from two production systems, one focused on the production of small to medium-sized flakes, the other devoted to the manufacture of large cutting tools. 21: Tighennif (formerly Ternifine), Argelia (~1.0 Ma; Sahnouni et al., 2018a), with Acheulian tools associated to remains of large mammals accumulated in a primary context. 22: Aïn Boucherit (2.4–1.9; Sahnouni et al., 2018b) and Aïn Hanech, Argelia (~1.7 Ma; Parés et al., 2014), which preserve Oldowan tools similar to those known at eastern African sites, as well as evidence of cutmarks and use-wear traces that indicate the exploitation by early *Homo* of animal tissues and marrow. 23: Oued Sarrat, Tunisia (~0.7 Ma; Martínez-Navarro et al., 2014b), which has yielded the oldest known cranium of *Bos primigenius,* associated with other small and large vertebrates, and six Acheulian tools. **(B)** Chronostratigraphic chart of Early Pleistocene to early Middle Pleistocene sites with evidence of hominin presence in Europe, North Africa, the Levantine Corridor, and the Caucasus. This chart shows the geochronological units, the land mammals' ages, the magnetostratigraphic units, and the biochronological units (French and Spanish biozones based on micromammals). Marine Isotope Stages (MIS) from Lisiecki and Raymo (2005). Biozones from Palombo (2010) and Minwer-Barakat et al. (2012).

area of alluvial and fluvial deposits as well as the glacis surface, is digitized with ImageJ for calculating the surface habitable by the terrestrial fauna. Based on this estimate, we deliver inferences on the size of the hominin population using the estimates of population density obtained for the hunter-gatherer groups of BL and FN3 (Rodríguez-Gómez et al., 2016a). This in turn leads us to discuss on the long-term viability of this hominin population and the discontinuity of the archeological record in the Guadix-Baza Depression.

RESULTS AND DISCUSSION

Hominin Subsistence Strategies in the Guadix-Baza Depression

The lithic assemblages from BL and FN3 are composed of abundant flakes of small size, cobbles (one third with percussion marks), cores, debris, and flake fragments. The flakes are largely made of flint and, to a lesser extent, of limestones and calcarenites from the surroundings of the sites. Flint was exploited for flake production whereas limestone, although used also for flake production, was mostly employed as percussion instruments (Barsky et al., 2010; Titton et al., 2018). Recently, Titton et al. (2021) indicated that BL is the oldest case reported of knapping and percussive activities on an ancient raw material reservoir deposit, because the analysis of the entire lithic collection of the site describes a tool kit composed of cores, flakes, debris, hammerstones, and other macro-tools like heavy-duty scrapers and sub-spheroidal morphologies. Moreover, the positioning of refitting items in the site points to *in situ* knapping (Toro-Moyano et al., 2013), which reaffirms the importance of BL as a raw material repository.

Many primates consume animal resources, but only humans regularly exploit animals the same size or larger than themselves (Butynski, 1982; Pobiner, 2020). Large ungulates represent concentrated packages of fat and protein, which are easily digestible and calorically rich macronutrients, and contribute micronutrients that are scarce in plants, such as heme-iron, folic acid and vitamin B12 (Thompson et al., 2019). Internal bone nutrients (e.g., brains and marrow) provide to humans the precursors to docosahexaenoic fatty acids and oleic acids, key for brain development and female reproductive success in hunter-gatherer societies (Plummer, 2004; Pobiner, 2020). This explains why the consumption of large ungulates was a fundamental component of the high-quality diet that allowed the evolutionary transformations that led to the genus *Homo* (e.g., reduction of postcanine teeth, brain expansion, enhanced cooperation with non-kin, and shorter interbirth intervals). For this reason, the tool-use/meat-eating package has been considered as inherently linked to the definition of *Homo* (Jiménez-Arenas et al., 2014; Thompson et al., 2019; Pobiner, 2020; however, for a recent criticism of the narrative that links the anatomical and behavioral traits of H. erectus to an increase in meat eating, see Barr et al., 2022).

The technological features of the lithic tools from BL and FN3, including the small dimensions of the flakes, allow discussing on carcass acquisition and processing by these hominins. This relates to the classic debate on *Homo* as a hunter or as a scavenger. During the eighties and nineties, most researchers interpreted the cut marks found in the Early Pleistocene sites of East Africa as evidence of defleshing activities by the Oldowan hominins of ungulate carcasses obtained through passive scavenging, which implied a secondary access to these resources (Binford, 1981, 1985; Blumenschine, 1986, 1987, 1991, 1995; Blumenschine and Selvaggio, 1988; Blumenschine et al., 1994; Capaldo, 1997; Selvaggio, 1998; Arribas and Palmqvist, 1999). In contrast, from the nineties onward a new scenario was considered, which envisaged the Oldowan hominins as having primary access to fully fleshed carcasses obtained from hunting or through active, confrontational scavenging (Bunn and Ezzo, 1993; Domínguez-Rodrigo, 1999; Bunn, 2001; Domínguez-Rodrigo and Piqueras, 2003; Domínguez-Rodrigo and Barba, 2006; Domínguez-Rodrigo et al., 2007, 2014; Bunn and Pickering, 2010). The reasoning, based on actualistic studies of predation, was as follows: although the large felids do not consume bone marrow contents, which opened to early *Homo* the opportunity to scavenge these resources, they exploit intensively the prey carcass, which results in a low availability of flesh. The lions of Tarangire National Park (Tanzania) are a good example: they efficiently deflesh small and medium-sized ungulate carcasses and in alluvial environments near water, they even thoroughly deflesh carcasses of prey heavier than 500 kg such as buffalo (Gidna et al., 2014). However, a study on the potential scavenging opportunities in Sweetwaters Game Reserve (Kenya), a conservancy area where lions face a low level of inter-specific

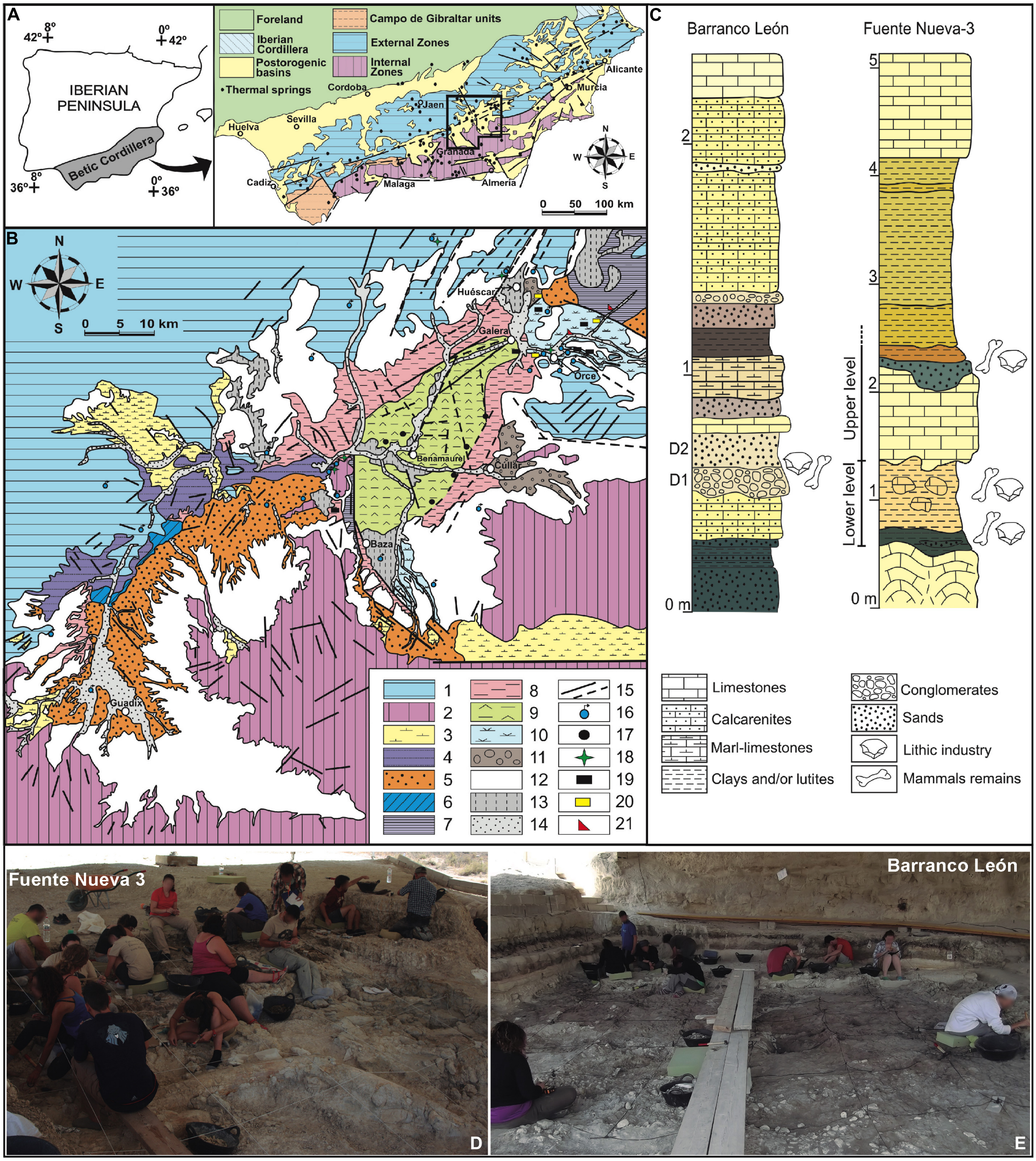

FIGURE 2 | **(A)** Geological context of the Guadix-Baza Depression in the Betic Cordillera, SE Spain. The box encloses the sedimentary basin. Black dots indicate the thermal springs (*N* = 122) that are nowadays active in the Betic Cordillera, with water output temperatures between 18 and 60°C. **(B)** Tectono-sedimentary map of the Guadix-Baza Depression with indication of those points that preserve geochemical, mineralogical or lithological evidence of thermal activity during the Neogene-Quaternary. Geological cartography updated from García-Aguilar et al. (2014, 2015: **Figure 1**, respectively). 1-External Zones, 2-Internal Zones, 3-Tortonian marine deposits, 4-Turolian alluvial and lacustrine deposits, 5-Plio-Pleistocene alluvial and fluvial deposits, 6-Pliocene lacustrine deposits of the Gorafe-Huélago sector, 7-Late Turolian-Ruscinian lacustrine deposits in the Baza Basin, 8-Middle Villafranchian fluvio-lacustrine deposits, 9-Middle Villafranchian lacustrine marls and evaporites, 10-Late Villafranchian lacustrine deposits, 11-Middle Pleistocene alluvial and lacustrine deposits, 12-Late Pleistocene glacis surface, 13-Holocene fluvial terrace, 14-Modern fluvial sediments, 15-Faults (solid lines; striped lines indicate those faults covered by sediments that have been inferred from aerial photographs), 16-Thermal springs nowadays active, 17-Sulfur deposits, 18-Travertine buildings, 19-Black levels, 20- Magnesium clays, and 21-Silexites. **(C)** Stratigraphic series of Barranco León (BL) and Fuente Nueva 3 (FN3) sites (adapted from Espigares et al. (2019)). **(D)** View of the excavation quarry of FN-3. **(E)** View of the excavation quarry of BL.

competition from hyenas, has shown that lions abandoned 95% of bones of large prey with at least some scavengeable flesh, and over 50% were left with large muscle masses. Moreover, while the scavengeable resources from fresh kills made by lions vary among prey carcasses, a single carcass of a large prey abandoned with only flesh scraps remaining (and all bone marrow contents intact) was usually substantial enough to satisfy the total daily caloric requirements of at least one adult male of *Homo erectus,* as exprapolated from an estimate for anatomically modern humans (Pobiner, 2015, 2020). This provides a solid argument for interpreting the Oldowan hominins as confrontational kleptoparasites or even as marginal, passive scavengers. However, human impact is high in Sweetwaters, and this could modify the behavior of lions, which deflesh their prey more thoroughly in those ecosystems where no modern humans threaten them (Gidna et al., 2014). In any case, Blumenschine and Pobiner (2007) estimated that the marrow that a hominin could extract from twelve long bones of an adult wildebeest carcass would represent 3,000 kcal, a value close to the daily energetic requirements of an adult early *Homo* (Aiello and Wells, 2002). In addition, Bickerton and Szathmáry (2011) suggested that the populations of *H. erectus* would have access to at least one elephant carcass resulting from natural death every month per 1000 km^2 foraged.

TABLE 1 | Faunal lists (large mammals only) from Venta Micena, Barranco León, and Fuente Nueva-3 (after Alberdi and Ruiz-Bustos, 1985; Moyà-Solà, 1987; Pons-Moyà, 1987; Martínez-Navarro, 1991; Torres Pérez-Hidalgo, 1992; Martínez-Navarro and Palmqvist, 1995; Martínez-Navarro et al., 1997, 2010, 2011, 2021; Cregut-Bonnoire, 1999; Martínez-Navarro and Rook, 2003; Abbazzi, 2010; Alberdi, 2010; Lacombat, 2010; Madurell-Malapeira et al., 2010, 2011; Medin et al., 2017; Bartolini-Lucenti and Madurell-Malapeira, 2020; Ros-Montoya et al., 2021; and references therein).

VENTA MICENA	BARRANCO LEÓN	FUENTE NUEVA-3
	Homo sp.	*Homo* sp. (only lithics)
Ursus etruscus	*Ursus etruscus*	*Ursus etruscus*
Lycaon lycaonoides	*Lycaon lycaonoides*	*Lycaon lycaonoides*
Canis orcensis	*Canis mosbachensis*	*Canis mosbachensis*
Vulpes alopecoides	*Vulpes alopecoides*	*Vulpes alopecoides*
Pachycrocuta brevirostris	*Pachycrocuta brevirostris*	*Pachycrocuta brevirostris*
Megantereon whitei	*Machairodontinae indet.*	*Megantereon whitei*
Homotherium latidens		Cf. *Homotherium* sp.
Panthera gombaszoegensis		
Lynx cf. *pardinus*		*Lynx* cf. *pardinus*
Meles meles	*Meles meles*	*Meles meles*
	Martellictis ardea	*Martellictis ardea*
Mammuthus meridionalis	*Mammuthus meridionalis*	*Mammuthus meridionalis*
Stephanorhinus cf. *hundsheimensis*	*Stephanorhinus hundsheimensis*	*Stephanorhinus hundsheimensis*
Equus altidens	*Equus altidens*	*Equus altidens*
	Equus sussenbornensis	*Equus sussenbornensis*
Hippopotamus antiquus	*Hippopotamus antiquus*	*Hippopotamus antiquus*
Bison sp.	*Bison* sp.	*Bison* sp.
Hemibos sp. cf. *H. gracilis*		
Praeovibos sp.		
Soergelia minor	*Ammotragus europaeus*	*Ammotragus europaeus*
Hemitragus albus	*Hemitragus albus*	*Hemitragus albus*
Caprini gen. et sp. indet.		
Praemegaceros cf. *verticornis*	*Praemegaceros* cf. *verticornis*	*Praemegaceros* cf. *verticornis*
Metacervocerus rhenanus	*Metacervocerus rhenanus*	*Metacervocerus rhenanus*
Capreolus sp.		

Sabertooths and Scavenging Opportunities for the Hominins

The hunting vs. scavenging debate was largely focused on the sequence of carcass access initially proposed for the bone assemblage from the FLK *Zinjanthropus* site at Olduvai, based on the frequency of tooth-marked and percussion-marked long bones of large mammals (Blumenschine, 1995; Capaldo, 1997; Selvaggio, 1998). The model considered a three-stage sequence of site formation: (i) in stage one, flesh-eating felids partially defleshed long bones, as deduced from the high frequency of tooth-marks on midshaft fragments; (ii) in stage two, hominins processed intact long bones for their marrow contents and left percussion marks, with the presence of cut marks indicating that the bones retained at this stage variable amounts of flesh; finally, (iii) in stage three, bone-cracking hyenas consumed long bone epiphyses for grease, as evidenced by the underrepresentation of these elements in the assemblage and the high percentage of tooth marks on the surviving epiphyses and the distal portions of the diaphyses (see discussion in Arribas and Palmqvist, 1999).

Domínguez-Rodrigo and Barba (2006) suggested that Blumenschine (1995) overestimated the number of long-bone midshafts with tooth marks in the FLK 22 assemblage due to the confusion of these marks with those resulting from microbial bioerosion, which would indicate primary access by the hominins to fully fleshed carcasses (but see criticism of their experimental procedure by Blumenschine et al. (2007)). The most recent analysis of the FLK 22 assemblage, using GIS techniques (Parkinson, 2018), has suggested that hominins had early access to largely fleshed carcasses, particularly those of smaller prey —which they may have primarily acquired through hunting— although patterns of bone damage on larger carcasses are consistent with secondary access through aggressive scavenging (Pobiner, 2020). In any case, we must bear in mind that the interpretive context that envisions the Oldowan hominins as primary hunters is based on experimental studies performed on modern felids, which thoroughly exploit the carcasses of their prey. This context does not apply to the Early Pleistocene hominin populations with Oldowan tools of Africa and Europe, where the predator guild was dominated by two sabertooths, *Megantereon whitei* and *Homotherium latidens* (Martínez-Navarro and Palmqvist, 1995, 1996; Arribas and Palmqvist, 1999; Palmqvist et al., 2022a).

Sabertooths have no living analogs and dominated the carnivore guild during most of the Cenozoic, filling the niche now occupied by the pantherine felids (Van Valkenburgh, 2001, 2007). Their long and laterally flattened upper canines were an adaptation for killing quickly megafaunal prey with deep wounds onto the prey throat rather than using the prolonged suffocating throat bite typical of the extant felines (Gonyea, 1976; Akersten, 1985; Anyonge, 1996a; Antón et al., 2004; McHenry et al., 2007; Christiansen, 2008; Meachen-Samuels and Van Valkenburgh, 2010; Salesa et al., 2010; Andersson et al., 2011; Meachen-Samuels, 2012). However, canine hypertrophy posed a biomechanical constraint on mandibular gape for delivering the killing bite, which involved a major reorganization of the skull to avoid over-stretching of the temporalis muscle during wide gaping (**Figure 3**) and led to a reduction of the premolar teeth. This is particularly evident in the African sabertooth *M. whitei,* which dispersed out of Africa by ∼1.8 Ma (Martínez-Navarro and Palmqvist, 1995, 1996; Palmqvist, 2002): compared to the less specialized *M. cultridens,* the species replaced in Europe by *M. whitei* during the late Early Pleistocene, the third lower premolar is reduced in *M. whitei* to a vestigial peg or even lost, while the fourth premolar and the paraconid of the carnassial are shortened but to a lesser degree, which reflects the greater enlargement of the sabers in the African species (Palmqvist et al., 2007). This resulted in lesser abilities to process the prey carcass and made it available more scavengeable resources for the hyenas and the hominins, which provides the ecological connection between the dispersal of *M. whitei* out of Africa and the first arrival of *Homo* in Europe, a continent where the survival of hominins during the cold season —with lowered plant resources compared to East Africa— depended on the regular scavenging of ungulate carcasses (Turner, 1992; Martínez-Navarro and Palmqvist, 1995, 1996; Arribas and Palmqvist, 1999; Martínez-Navarro, 2004, 2010; Palmqvist et al., 2007, 2022a).

Microwear analyses of canines and carnassials provides additional evidence on the lower ability of sabertooths to process the prey carcass. A comparison of the frequency of pits and scratches in the canines of the North American *Smilodon fatalis* and other living carnivores with disparate feeding and hunting repertoires (e.g., spotted hyenas, lions, cheetahs, and wild dogs) showed that these teeth were used by *S. fatalis* for prey killing and avoided contact with bone during prey consumption (Anyonge, 1996b). In the case of the wear facet of the carnassials, which are employed exclusively in food processing, the bone-cracking hyenas exhibit few long scratches and a high proportion of pits to scratches, while the cheetah (which feeds exclusively on soft organs and only consumes bones of small prey; Schaller, 1968; Brain, 1981; Skinner and Smithers, 1990) shows a predominance of narrow scratches with very few pits. Strikingly, the microwear pattern of *S. fatalis* showed relatively narrow and long scratches combined with an extremely low frequency of pits, even lower than in the cheetah (Van Valkenburgh et al., 1990). This suggests that sabertooths probably consumed even less bone than the cheetah to prevent canine breakage, which means that their prey carcasses would retain a significant fraction of scavengeable resources (Van Valkenburgh et al., 1990).

The elongated, laterally flattened canines of sabertooths were optimal for killing large prey, but also were more vulnerable to fracture than the shorter and conical canines of the living felids due to the unpredictable loads generated in prey stabilization during the killing bite (Van Valkenburgh and Hertel, 1993; Van Valkenburgh, 2009). This made the heavily muscled forelimbs of sabertooths imperative for pulling down and immobilizing prey before positioning the killing bite (Gonyea, 1976; Akersten, 1985; Anyonge, 1996a; Antón et al., 2004; Christiansen, 2008; Salesa et al., 2010; Andersson et al., 2011; Meachen-Samuels, 2012). The latter is reflected in the short and robust forelimb bones of *S. fatalis,* reinforced by cortical thickening, which allowed it to minimize prey struggling, helping to position the killing bite carefully to avoid contact with bone (Meachen-Samuels and Van Valkenburgh, 2010; Martín-Serra et al., 2017). A comparative study of the skulls of *S. fatalis* and the lion based on finite element analysis showed that the sabertooth skull was less equipped to resist the forces generated by a struggling prey, which pointed to rapid slashing bites during prey killing (McHenry et al., 2007). In contrast, the lion uses its stouter canines to hold a suffocating bite in the snout of large prey such as buffalo, which explains that the forelimbs are less important for subduing prey (Salesa et al., 2010; Meachen-Samuels, 2012; Martín-Serra et al., 2017). Moreover, Figueirido et al. (2018) showed that the rostrum of *S. fatalis* was almost entirely composed of cortical bone (which supports better directed loads) while the lion skull had a substatinal amount of trabecular bone (which can support unpredicted and multidirectional forces). This indicated that the skull of *S. fatalis* was well-equipped to deliver a quick killing-shear bite, but it could not withstand the unpredictable forces generated when feeding on bones (Figueirido et al., 2018).

The highly derived craniodental and postcranial anatomy of sabertooths suggests that the pantherine felids cannot be considered as their modern functional analogs, because sabertooths: (i) were able to hunt larger ungulate prey relative to their body size, exerting a higher predation pressure on the juveniles of megafauna; and (ii) exploited their prey to a lesser extent, which would have resulted in greater amounts of flesh abandoned in the prey carcass (Binford, 1980, 1981; Marean and Ehrhardt, 1995; Arribas and Palmqvist, 1999; Palmqvist et al., 2003, 2007, 2011, 2022a,b; Ripple and Van Valkenburgh, 2010; Martínez-Navarro et al., 2014a; Van Valkenburgh et al., 2016; Martín-Serra et al., 2017; Martínez-Navarro, 2018). These resources would in turn be available for the scavengers, including the hominins and hyenas, as documented at FN3 (Espigares et al., 2013, 2019; Yravedra et al., 2021). This interpretation makes sense if we consider the lack of an effective weaponry in the Oldowan hominins for subduing large prey with their small flint flakes and cores, or for driving predators from their kills acting as kleptoparasites (Potts, 1991; Blumenschine and Pobiner, 2007; Treves and Palmqvist, 2007). However, throwing stones for driving away carnivores and stealing their prey would be always a possibility, as suggested by Lordkipanidze (2015) for explaining the abundant allochtonous cobbles found in Dmanisi (Coil et al., 2020). Interestingly, manuports of dolomitic limestone are abundantly represented in FN3 (Espigares et al., 2013).

While it has been argued that expanding group sizes prompted Acheulean hominins to become big game hunters (Martínez-Navarro, 2018), perhaps including elephants as their prey (Agam and Barkai, 2018), it is difficult to conceive that the limited technological skills of the Oldowan hominins allowed them to prey on megafauna. Therefore, it is thus more reasonable to consider that Early *Homo* initially expanded its diet from the major reliance on plant foods of australopithecines to scavenging

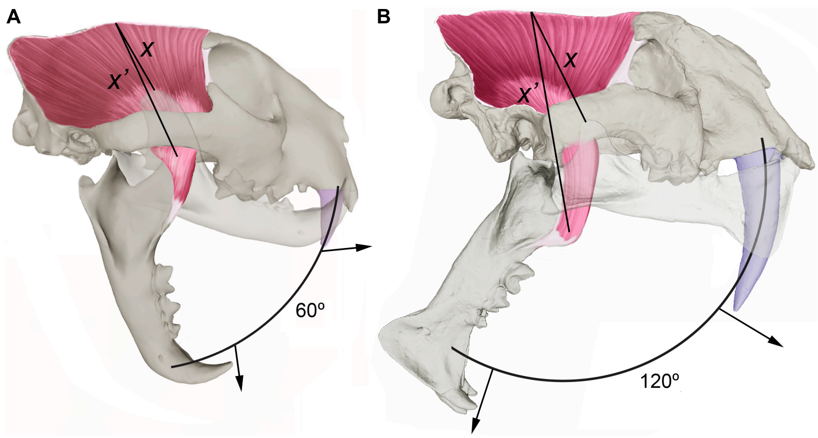

FIGURE 3 | Comparison of the craniodental anatomy of a leopard, *Panthera pardus* **(A)**, with a sabertooth, *Megantereon nihowanensis* **(B)**. The lines X and X′ measure the stretching of temporalis muscle from the tip of the coronoid process to the sagittal crest with the jaw closed and open, respectively. The elongation of the upper canines of sabertooths posed a severe biomechanical constraint on mandibular gape for delivering the killing bite, which involved a major reorganization of the temporalis to avoid over-stretching of the muscle fibers during wide gaping. This was achieved by a number of changes in their craniodental anatomy compared to the pantherine felids (Emerson and Radinsky, 1980; Akersten, 1985; Palmqvist et al., 2007; Slater and Van Valkenburgh, 2008; Figueirido et al., 2011; DeSantis et al., 2021): (i) a lowered glenoid fossa; (ii) a shortened coronoid process and a laterally shifted angular process; (iii) a less laterally projected postglenoid process; (iv) an upwardly rotated palate; (v) a shorter and narrower temporal fossa; (vi) a more vertical occiput; and (vi) a protruding incisor arcade, which independized the hypertrophied upper canines from the incisors. Such skull reorganization resulted in a narrowing of the temporalis fibers and their more perpendicular orientation to the tooth row, which allowed to increase jaw gape up to 180° in sabertooths while retaining a degree of muscle stretch like that of pantherine felids. Moreover, the masseter muscle, which exerts its maximum force at smaller gapes, was also reduced. Panel **(A)** shows that with a jaw gape of 60°, the degree of muscle stretching of the temporalis (measured by the ratio between X′ and X) in the leopard (∼85%) is like in *Megantereon* **(B)** with a gape of 120° (∼80%). A result of this major skull reorganization in sabertooths was that the point of maximum bite force exerted at the carnassial was positioned more backwardly, which led to a reduction of the post-canine dentition not related to the slicing function of the carnassial. The protruding incisor arcade of sabertooths **(B)** helped these predators to avoid canine breakage when feeding on the prey carcass because it independized the function of the incisors, used to tear chunks of flesh from the prey carcass (a task performed in modern felids by their stout, conically shaped canines), from the function of the canines, employed to deliver deep wounds during prey dispatch (Biknevicius et al., 1996). Thus, prevention of canine breakage during prey killing and feeding encounters was a strong selective agent in sabertooths and suggests that a non-scavenging behavior was a clear ecological limitation posed by their hypertrophied upper canines.

bone marrow, brains and meat (Ben-Dor et al., 2021). Therefore, the trophic level of *Homo* probably evolved from a low base to a high carnivorous position during the Pleistocene, beginning with *H. habilis* as a scavenger and peaking in *H. erectus* as a hunter (Ben-Dor et al., 2021; but see Barr et al. (2022)).

Megaherbivores like adult elephants, hippos and rhinos are often regarded as invulnerable to predation, but it has been suggested that lions regularly hunted such large prey during the Pleistocene (Guthrie, 1990). Lion prides have been documented today hunting elephants, mostly juveniles, in high frequencies in those environments where other ungulates are scarce, like the Savuti area of Chobe National Park, Botswana (Joubert, 2006; Power and Shem-Compion, 2009). However, lions preferentially prey on medium-to-large ungulates when they are abundant (Schaller, 1972), within a weight range of 190–550 kg (Hayward and Kerley, 2005), and only occasionally hunt megafauna (Palmqvist et al., 1996). In fact, elephants are rarely preyed upon by lions (Skinner and Smithers, 1990) and when this does occur it involves yearling calves weakened by drought (Loveridge et al., 2006) or older animals wounded by poaching (Ruggiero, 1991).

Passive scavenging of ungulate carcasses partially defleshed by sabertooths would have enhanced the survival of the hominins of Guadix-Baza during Early Pleistocene times (Martínez-Navarro and Palmqvist, 1996; Arribas and Palmqvist, 1999; Martínez-Navarro, 2004, 2010; Palmqvist et al., 2005, 2007; Espigares et al., 2013, 2019; Martínez-Navarro et al., 2014a; Rodríguez-Gómez et al., 2016a, 2017a). We propose here that they probably exploited a wide repertoire of subsistence strategies, including: (i) the opportunistic hunting of small-sized mammals and other vertebrates (e.g., amphibians and reptiles); (ii) the kleptoparasitism of the prey of primary predators like sabertooths and wild dogs; and (iii) the opportunistic scavenging of carcasses of very large animals not exposed in life to predation that died from other causes, although this is a rather speculative issue. The latter possibility is supported by evidence of competition between *Homo* sp. and *P. brevirostris* for the exploitation of a carcass of an old individual of elephant *Mammuthus meridionalis* in the upper archeological level of FN3: the skeleton of this elephant is dismembered and surrounded in part by flint flakes and coprolites, which suggests a sequential pattern of consumption by the hominins and hyenas (Espigares et al., 2013).

A mathematical model that evaluates the sustainability of the community of secondary consumers, based on the biomass of primary consumers potentially available (Rodríguez-Gómez et al., 2013, 2014a,b, 2016b, 2020), has provided relevant data on the hominin population that inhabited Guadix-Baza (Rodríguez-Gómez et al., 2016a). The model estimates: (i) the age structure and mortality rate that make the population of each primary consumer stable; (ii) the distribution of individuals

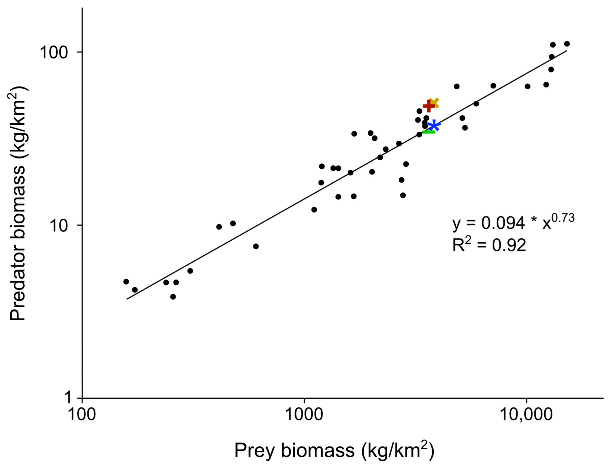

FIGURE 4 | Relationship between the biomass of predators and prey in modern ecosystems (data from Hatton et al. (2015)) and ranges of estimates of predator and prey biomass values obtained for the Orce sites [data from Rodríguez-Gómez et al. (2016a, 2017a)]. Fossil assemblages: Barranco León/Fuente Nueva 3 (maximum: red cross, minimum: green dash) and Venta Micena (maximum: yellow ex, minimum: blue asterisk). Least-squares regression equation derived with software SPSS v. 25.

among size categories; (iii) the biomass that the secondary consumers can extract from these populations in the long term; and (iv) resource distribution among the members of the carnivore guild. In the case of hominins, the model considered a dietary contribution of 30% of animal resources, in agreement with the diet of modern hunter-gatherer populations at temperate latitudes (Rodríguez-Gómez et al., 2016a). The hunting and scavenging scenarios were both modeled for estimating the population density of *Homo* sp. in Guadix-Baza. This suggested a scavenging behavior as optimal for the population, which would hold 12 individuals per 100 km^2 during a year, a value close to the mean density of modern hunter-gatherers (Binford, 2001; Marlowe, 2005). The density estimated for a strict hunting behavior was slightly lower, 9.5 individuals/100 km^2 (Rodríguez-Gómez et al., 2016a). Given that both estimates are similar, to consider a scavenging or a hunting behavior has little effect on the size of the hominin population of the basin, as noted above. The densities estimated for the hominins and carnivores in the Orce sites (**Figure 4**) agree with the prey/predator biomass ratios derived with the equation of Hatton et al. (2015).

"Meat made us humans" is a recurrent topic in any debate on the subsistence strategies of hominins (Bunn, 1981, 2007; Stanford, 1999; Bunn et al., 2017). This relates to the evolutionary trend toward increasing encephalization in the genus *Homo,* because the high maintenance cost of the nervous system involved a reduction of the digestive tract and a shift toward a more carnivore diet compared to the australopithecines (Leonard and Robertson, 1994, 1996; Aiello and Wheeler, 1995; Jiménez-Arenas et al., 2014). However, the subsistence strategies of early *Homo* probably included a broader spectrum of resources (e.g., small mammals, birds, herpetofauna, invertebrates, eggs, honey, and edible vegetation) that do not leave archeological evidence (Blasco et al., 2011; Hardy et al., 2017; Prado-Nóvoa et al., 2017; Espigares et al., 2019), as happens in the case of modern hunter-gatherers like the !Kung of the Kalahari Desert and the Hadza of northern Tanzania (Woodburn, 1968; Ho et al., 1972; Lee, 1979; Silberbauer, 1981; O'Connell et al., 1988; Hawkes et al., 1991; Cordain et al., 2000; Binford, 2001; Bunn, 2001; Marlowe, 2005). Lee (1968), Cordain et al. (2000), and Marlowe (2005) have shown a negative correlation between gathering and latitude due to the decrease with latitude in the availability of edible plants. In contrast, gathering is the dominant mode of subsistence in latitudes like those of the Orce sites. In the Baza Basin, freshwater fish could have also been a regular source of long-chain polyunsaturated fatty acids (e.g., omega n-3, n-6 and docosahexaenoic acids) that are essential for the early development of the brain, retina and other neural tissues (Uauy et al., 2001; Kuipers et al., 2010).

There is a lack of knowledge on the vegetal resources available at the Orce sites, as all attempts to extract fossil palynomorphs from the sediment were unsuccessful and even the coprolites of hyena analyzed were palynologically sterile (Carrión, 2002; Carrión et al., 2009). Despite this, inferences on the past vegetation of the basin have been derived from δ^{13}C and δ^{15}N isotopes in the bone collagen of the herbivores of VM (Palmqvist et al., 2003, 2008a,b), which allowed to infer their feeding habits. Specifically, the species (**Table 1**) were classified among: (i) browsers (rhino *Stephanorhinus hundsheimensis* and deer *Praemegaceros verticornis*); (ii) mix-feeders (ovibovine *Soergelia minor* and deer *Metacervocerus rhenanus*); and (iii) grazers (horse *Equus altidens, Bison* sp., muskox *Praeovibos* sp., goat *Hemitragus albus,* and *M. meridionalis*). The predominance of taxa adapted to grazing in open habitat agrees with: (i) the synecological reconstruction of this paleocommunity as a plain with bush/forest patches (Mendoza et al., 2005; Saarinen et al., 2021); and (ii) the estimate of ∼780 mm of annual rainfall derived from the range of δ^{15}N values in the ungulates that fed on terrestrial vegetation (García-Aguilar et al., 2014), which is close to the estimate of ∼750 mm obtained from the herpetofauna of BL and FN3 (Blain et al., 2016). According to Blain et al. (2021), the first hominin occupations in Western Europe (e.g., BL/FN3 and TE9) would correspond to warm and humid conditions in an open 'savanna' environment with 20–25% wood. A study of the herpetofaunal assemblages of BL and FN3 has indicated different conditions for the levels with the highest density of anthropic evidence at these sites: a humid, wooded biotope for BL and a more open and drier biotope for FN3 (Sánchez-Bandera et al., 2020).

Most ungulate species present at VM are also represented in the faunal assemblages of BL and FN3 (**Table 1**). The exceptions are the mesodont *S. minor,* which is replaced by the hypsodont caprine *Ammotragus europaeus,* and the presence of a second equid species, the large-sized horse *Equus sussenbornensis* (Moullé et al., 2004; Alberdi, 2010; Martínez-Navarro et al., 2010). Hindgut fermenters process a large volume of food in a short time and can feed on low quality grasses too fibrous for a ruminant to subsist on (Janis, 1976; Janis et al., 1984; Duncan et al., 1990). For this reason, the presence of two hypergrazing equids in BL and FN3 suggests more arid conditions and an herbage of lower quality than in VM (Palmqvist et al., 2008a). This would result in a decrease in the abundance of fruits and other succulent plant stuffs for the hominins, which would make them more dependent on animal resources.

Hominin and Carnivore Involvement in Barranco León and Fuente Nueva 3

Espigares et al. (2019) reported on the cut marks and percussion marks identified in BL and FN3 (see also Yravedra et al. (2021) for FN3). Tooth marks produced by carnivores, particularly the hyena *P. brevirostris,* were also found in the bone assemblages of both sites, but at lower frequencies than in the hyena den of VM (Palmqvist et al., 1996, 2005, 2011, 2022b; Luzón et al., 2021). To evaluate the contribution of hominins and carnivores to the site formation process in BL and FN3, we have performed here a study on the abundance of limb bone epiphyses and compared the results with those for VM.

Figure 5 shows the relationship between the abundance of epiphyses of major limb bones and their estimated marrow yields in the three Orce sites. The regressions for BL and FN3 show an inverse, statistically significant relationship between bone survival and marrow contents (r = 0.624, p = 0.05 for BL; r = 0.682, p = 0.03 for FN3), which indicates that the hominins preferentially fractured the anatomical portions with greater nutritional value. However, these regression lines show considerable scatter, as reflected in their wide confidence 95% intervals. There is also a negative relationship in VM, but much closer in statistical terms (r = 0.885, p = 0.001), which shows a greater selectivity in bone fracturing by the hyenas. **Figure 6** shows the positive relationship between bone survival and mineral density in the three sites. Again, BL and FN3 show lower levels of statistical significance (r = 0.636, p = 0.003 for BL; r = 0.548, p = 0.015 for FN3) and more scatter around the regression lines than VM (r = 0.745, $p < 0.0001$ for VM).

Marrow determines the interest of the bone collecting and modifying agent on the nutritional contents of the skeletal remains, while mineral density is behind the effort invested in accessing these resources. The hominins fractured the bones in BL and FN3 using stones, a task relatively straightforward that did not represent a major effort, which originated percussion marks (Espigares et al., 2019; Yravedra et al., 2021). Therefore, it is not expected that they were highly selective in their choice of the bones to be fractured, apart from focusing more on the remains that provided more marrow. However, hyenas fractured the bones in VM using their robust premolar teeth assisted by their massive jaws (Palmqvist et al., 2011), which resulted in abundant spiral and longitudinal fractures (Arribas and Palmqvist, 1998). Hyenas were at risk of breaking their teeth or dislocating their jaws while fracturing the densest bones, which forced them to be more selective than the hominins (who risked nothing when fracturing bones with stones). Thus, our results suggest that although BL and FN3 record evidence of hominin and carnivore activity, the main agent involved in the accumulation and modification of the remains preserved at both sites were the hominins.

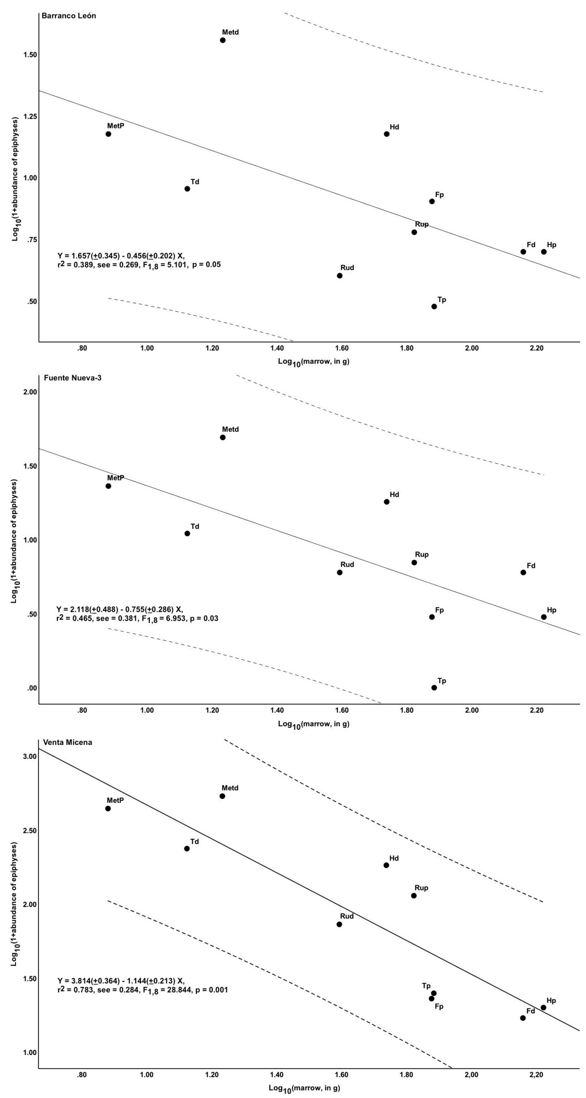

FIGURE 5 | Relationship between the survival of major limb bone epiphyses and their estimated marrow contents (mean for modern horse and bison; Outram and Rowley-Conwy, 1988; Brink, 1997) in BL, FN3, and VM. H, Humerus; Ru, Radius/ulnae; F, Femur; T, Tibia; Met, Metapodials; p, Proximal; d, Distal. Striped lines represent the 95% confidence intervals below and above the regression lines. Least-squares regression equations derived with software SPSS v. 25.

The hyena *P. brevirostris,* the jackal-sized *Canis mosbachensis* and a large-sized crow (unpublished specimen VM-3121, preliminarily classified as *Corvus* sp.; by the moment, this species has not been identified in BL and FN3) were indeed worthy competitors of the hominins for carrion in BL and FN3. Soaring at high altitude is an energetically efficient mode of locomotion, which allows vultures to cover huge distances and discover carcasses by sight or watching the movements of other neighboring birds such as crows (Palmqvist and Vizcaíno, 2003). Hyenas and jackals often rely upon visual clues such as circling vultures to identify scavengeable resources, and then run long

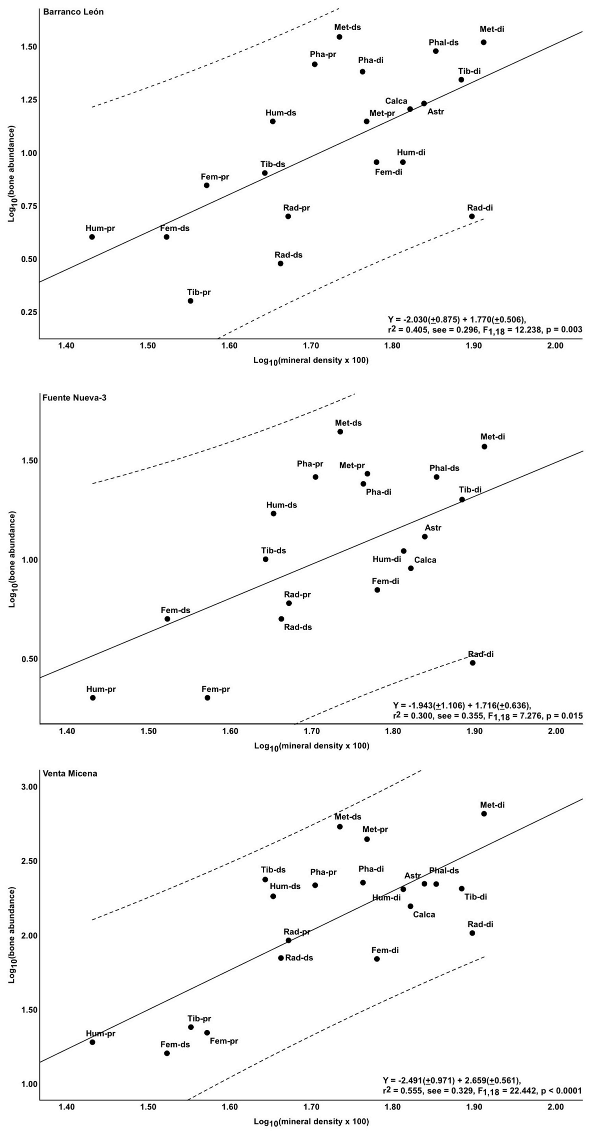

FIGURE 6 | Relationship between the survival of skeletal remains and their estimated mineral density (mean for modern horse, gnu and raindeer; Lam et al., 1999) in BL, FN3, and VM. Hum, Humerus; Rad, Radius; Fem, Femur; Tib, Tibia; Met, Metapodials; Astr, Astragalus; Calca, Calcaneum; Pha, Phalanges; pr, Proximal; di, Diaphysis; ds, Distal. Striped lines represent the 95% confidence intervals below and above the regression lines. Least-squares regression equations derived with software SPSS v. 25.

distances to secure the carcass (Bramble and Lieberman, 2004). However, they do not perform well running at long distances, as they need to rest after relatively short distances to breathe and cool down. In contrast, humans are comparatively poor sprinters but are well adapted for endurance running (i.e., running many kilometers at relatively low speed over extended time periods using aerobic metabolism) (Bramble and Lieberman, 2004; Lieberman et al., 2007; Pickering and Bunn, 2007; Liebenberg, 2008; Ruxton and Wilkinson, 2012). This results in an advantage for scavenging in open habitats during the day, particularly during the dry season, when other terrestrial scavengers are prevented from running long distances due to thermoregulatory constraints (Lieberman et al., 2007). Endurance running may have allowed early *Homo* to reach carcasses before other terrestrial scavengers and to exploit them until surrendering them on the arrival of potentially dangerous hyenas. However, the advantages of endurance running are not unanimously accepted. Pickering and Bunn (2007) argued that endurance running: (i) would have required for hunting that in the absence of visual contact, hominins had the ability to track prey; (ii) is not common among modern foragers except for very open and hot habitats, because it is a physically demanding activity; and (iii) scavenging in modern riparian woodland habitats would result in a low competition intensity for carcasses. These arguments are based on two flawed assumptions, the presumptive link between modern human-like cognition and tracking abilities, as well as the notion that the limited (and biased) modern ethnographic record provides an adequate reflection of past behaviors (Lieberman et al., 2007).

Hominins entered the carnivore guild when they became scavengers (and later hunters), which forced them to compete with other carnivores using a combination of strength, speed, stealth, and cooperation. Modern foragers are no exception in this, as a high percentage of scavenging opportunities observed among Hadza and other hunter-gatherers involve power scavenging for driving off lions or hyenas from their kills using simple weapons like sticks and stones (Potts, 1991; Blumenschine and Pobiner, 2007; Lieberman et al., 2007). Given that early *Homo* was neither strong nor powerful, and apparently lacked projectile weapons, it is debatable whether they could engage in competition scavenging with dangerous carnivores (Potts, 1991; Lieberman et al., 2007). Therefore, persistence hunting and scavenging may have been more common before the invention of the bow-and-arrow or the domestication of dogs and horses (Liebenberg, 2008).

Domínguez-Rodrigo and Organista (2007) proposed the use of the following ratios for evaluating the degree of ravaging intensity in an assemblage: (i) axial bones to appendicular ones, which would range from 4.25 for a carcass transported complete or died in a setting devoid of competition among carnivores, to 0 for a completely ravaged skeleton; (ii) femur to tibia, which would range from 1 in a ravaging-free assemblage to 0 in one with maximum ravaging intensity; and (iii) proximal humerus plus distal radius to distal humerus plus proximal radius, which relates to the relative abundance of the least dense bone portions (preferentially consumed by the carnivores) to the densest ones, and takes a value between 1 in an undisturbed carcass and 0 in the situation of highest ravaging. The second ratio is only relevant if carnivores had primary access to complete bones and not to bones already broken by hominins (Domínguez-Rodrigo and Organista, 2007). In the latter case, when taphonomic evidence indicates that the hominins broke long limb bones (as in BL and FN3) and only bone portions instead of whole bones were available for ravaging, they recommend the third ratio as the most informative.

Girdle and limb bones are between three and five times more abundant at the hyena den of VM than vertebrae and ribs, depending on the excavation quarry analyzed (García-Aguilar et al., 2015; Luzón et al., 2021; Palmqvist et al., 2022b). Ribs are scarcely represented at VM by small fragments and are even less abundant in BL and FN3 (Espigares, 2010). The ratio of ribs, vertebrae and girdle bones to limb bones is 17.9% (52/290) in BL and 11.8% (35/296) in FN3, figures that compare well with VM, 13.5% (532/3,942). In VM, the overrepresentation of the elements of the appendicular skeleton over those of the axial skeleton indicates the dismemberment by hyenas of the ungulate carcasses scavenged and the preferential transport of the limbs to their denning sites (Palmqvist and Arribas, 2001). Our data suggest that the assemblages of BL and FN3 were also biased by the selective transport of remains by the hominins, who were focused to marrow extraction of the remains in a safe place (Espigares et al., 2013). The third ratio shows similar values in the three sites: 0.37 (7/19) in BL, 0.30 (7/23) in FN3 and 0.32 (89/274) in VM. In contrast, there are differences in the values of the ratio of femur to tibia: 0.63 (20/32) in BL, 0.47 (14/30) in FN3 and 0.23 (107/465) in VM. This suggests that the hominins broke the major limb bones in BL and FN3 for exploiting their marrow contents and this led to the loss of the resource that would make them more attractive to the hyenas, thus explaining their better preservation in BL and FN3 than in VM.

Early Pleistocene Environments of the Guadix-Baza Depression

In the Early Pleistocene, the environments of the Baza Basin were dominated by shallow lacustrine systems fed by the precipitation of meteoric waters on the lake surface as well as by the contribution of alluvial waters and thermal springs (García-Aguilar and Palmqvist, 2011; García-Aguilar et al., 2014, 2015). This led to deposits of marls, calcilutites, limestones, evaporites, sands, and dark lutites (**Figure 2B**). The lacustrine systems were dynamic in both time and space, as evidenced by the lateral wedging of the facies linked to these environments, which resulted in the appearance of non-flooded areas inhabited by the mammalian community and the hominins.

The cartography of the Late Villafranchian deposits that correspond to the archeological levels of BL and FN3 allows reconstructing their paleogeographic context (**Figure 7**). This was characterized by large flood plains crisscrossed by channels in the Guadix Basin as well as in the W and SW sectors of the Baza Basin, with a lacustrine system that spread through the N and NE sectors of the Baza Basin (Cortes de Baza-Huéscar-Orce sector, **Figure 2B**). The lacustrine deposits represent a stratigraphic unit with a maximum thickness of 40 m (up to 50–60 m in the lake depocenter), which preserves the main sites of Orce. The unit shows an alternation of levels of marls-calcilutites and limestones, each one meter thick on average, with intercalations of thin levels of dark lutites and detritic facies (conglomerates and sands) to the lake borders (García-Aguilar et al., 2014).

Several mollusks (gastropods *Bithynia tentaculata, Hydrobia* aff. *acuta, Melanoides tuberculata,* and *Gyraulus* cf. *laevis;* bivalve *Pisidium casertanum;* **Figures 8E–I**) indicate the presence of an euryhaline environment in BL (Albesa and Robles, 2020). The lacustrine sediments of BL preserve shells of two ostracods, *Candona* sp. and *Cyprideis torosa* (Anadón et al., 1994), which live in oligo- to mesosaline conditions (**Figures 8A,B**). The limits of tolerance to salinity of these species provide clues on the lake waters: *B. tentaculate, H. acuta*, and *M. tuberculata* can live with elevated salinities (12–30‰), but their optimum is lower (0.2–3‰ for *M. tuberculata*). In contrast, *P. casertanum* and *G. laevis* tolerate salinities of only up to 3–5‰ (Albesa and Robles, 2020). This indicates a thermophile lacustrine environment with alternating phases of salinity, from freshwater to moderately brackish conditions in the lake waters and higher values of salinity in the surrounding swampy areas. Such inference agrees with (i) the presence in the sediments of microcrystalline gypsum originated by neoformation (García-Aguilar et al., 2014); (ii) the high $\delta^{15}N$ values measured in the bone collagen of *Hippopotamus antiquus,* a species that fed on the aquatic macrophytes that grew in the oligosaline waters of the lakes instead of consuming terrestrial grasses, as does the living *H. amphibius* (Palmqvist et al., 2003, 2008a,b, 2022a; García-Aguilar et al., 2014); and (iii) the finding of a common Shelduck (*Tadorna tadorna*) in VM (**Figure 8J**). This waterfowl dwells in coastal mudflats and lagoons, estuaries, and riverine environments of Europe, generally occurring in salt or brackish water, where it feeds mostly on saltwater snail *H. acuta* (Carboneras and Kirwan, 2018), a species that can survive at salinities of up to 39‰ (Britton, 1985). In the case of VM, the ostracodes *Ilyocypris bradyi* and *I. gibba* (**Figures 8C,D**) provide additional information on the paleoenvironment: the former lives in high energy streams with abundant underwater vegetation, while the latter evidences shallow lake borders with warm and fresh to oligosaline waters, a sandy substrate and lushy vegetation (Martínez-García et al., 2015, 2017).

The detritic facies of the Baza Basin are composed of sands and silts originated in organic-rich coastal lacustrine environments and emerged plains, although they can also correspond to distal riverine systems (García-Aguilar et al., 2014). Some sandy and silty deposits are associated with conglomerates, which represent flood deposits that penetrated the lakes as highly disorganized deltas (e.g., level D of BL; Arribas and Palmqvist, 2002).

The estimates of prey biomass (kg/km^2) for the Orce sites (**Figure 9**), obtained with the Weibull model following the procedure described by Martín-González et al. (2019) and Rodríguez-Gómez et al. (2022), are lower than those measured in several African Natural Parks and Game Reserves, like Ngorongoro Crater or Amboseli, close to those of Masai Mara, Savuti, Hluhluwe Imfolozi or the Nwaswitshaka River, and higher than in Serengeti, Selous or the Okavango Delta, among many others. This figure shows a direct relationship of prey biomass with annual rainfall (**Figure 9A**), but not with mean annual temperature (**Figure 9B**). Prey biomass estimates suggest that meat availability was high in the Orce sites, particularly compared with most sites of Atapuerca. The only exceptions are TD6-1,2 and TD8, in which the estimates are only slightly lower than in BL and FN3. In fact, a comparison of the faunal assemblages of Atapuerca showed that TD6-1,2 and TD8 were the levels with lowest competition intensity among the secondary consumers (Rodríguez-Gómez et al., 2013, 2014a, 2017b), even lower than in VM, BL and FN3. This indicates

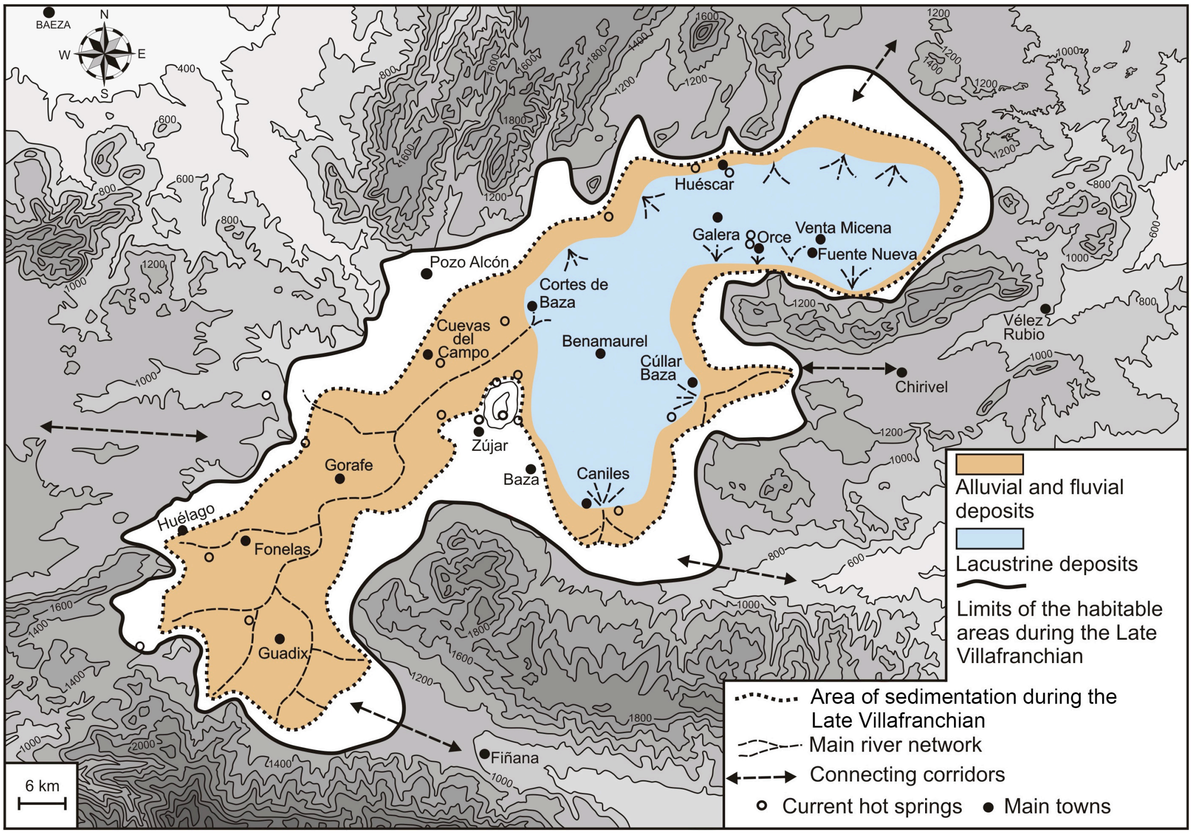

FIGURE 7 | Reconstruction of the paleoenvironments of the Guadix-Baza Depression based on the cartographic extent of the Late Villafranchian sediments of the basin depicted in **Figure 1B** (for the stratigraphic series sampled, see García-Aguilar et al. (2014): **Figure 3**). The connecting corridors indicated by arrows are those open during the late Early Pleistocene, when the sedimentary basin was endorheic. The hydrographic network of the basin was captured in the late Middle Pleistocene by the Guadiana Menor River, a tributary of the Guadalquivir River. This led to a stage in which erosion dominated over sedimentation (i.e., a transit from an endorheic regime to an exorheic one). For this reason, the current topography that surrounds the depression shows a corridor to the west of the town of Pozo Alcón, but this connection did not exist during the late Early Pleistocene.

that, departing from a similar prey biomass, the Orce ecosystems supported a more diverse predatory guild than those recorded at TD6-1,2 and TD8 (Rodríguez-Gómez et al., 2016a, 2017a). Based on a comparison between these results and those derived with the equations of Rodríguez et al. (2014) to estimate the maximum carrying capacity of the ecosystems of Orce and Atapuerca, Rodríguez-Gómez et al. (2022) proposed that the differences in secondary production between these sites could result from the exceptional geological conditions of Guadix-Baza, particularly the presence of thermal springs that provided a mild and productive paleoenvironment throughout the year (García-Aguilar and Palmqvist, 2011; García-Aguilar et al., 2013, 2014, 2015).

Figure 7 shows the paleogeographic model of Guadix-Baza during the late Early Pleistocene, based on cartographic data of the sedimentary deposits (**Figure 2B**). The outer perimeter of the basin, which corresponds to the limits of the surface emerged and the one covered by the lake waters, encloses an area of 4,050 km^2. This encompasses the outcrop area of alluvial and fluvial deposits (i.e., flood plains, proximal zones of the alluvial systems and alluvial fans, covered by water only during the rainy episodes) and the glacis surface, which includes the area with a gentle slope in the foothills situated up to a height of 20 m over this surface. This represents a living area for the terrestrial fauna and the hominins of 2,925 km^2, while the outcrop area of the lacustrine deposits covers 1,125 km^2. The extent of the lake would fluctuate between low-stand stages, which correspond to the limestone and marly limestone beds deposited during the drops of the water table, and high-stand stages, which evidence the rising of the water table that resulted in the deposit of marls and calcilutites. The emerged area inhabited by the terrestrial fauna would be greater during the low-stand stages, when the alluvial feeding of the lake originated in the southern and eastern reliefs was scarce and of low energy. Given the limited depth of the lacustrine system (~2 m on average, with large areas on the swampy environments of the lake margins showing a decametric depth), the lowering of the water table would result in wide emerged areas in the lake surroundings. The opposite situation would apply to the high-stand stages, when higher precipitations and a greater recharge of the lake by alluvial waters originated in the perimeter of the basin took place. This would result in a more restricted extent of the terrestrial ecosystems. Low-stand to high-stand fluctuations would encompass the periodic changes between warm-moist and cold-dry conditions of climatic cycles, which would represent variations in the living area for the terrestrial fauna of 20–25% above (low-stand) and below (high-stand) the cartographic extent of the deposits drawn in **Figure 7**. Moreover, there would be also yearly oscillations in the extent of the water sheet between the winter and summer seasons. Finally, **Figure 7** shows the sedimentary depression during the late Early Pleistocene as a closed, endorheic basin with internal drainage, but with a limited number of connecting corridors for the terrestrial fauna to other surrounding areas, especially to the East. For this reason, the ecological scenario of the Orce sector of the sedimentary depression (a satellite basin of $\sim$170 km^2) resembles the one found in the Ngorongoro Crater, Tanzania, which has a similar extent ($\sim$230 km^2) and hydrothermal context (Deocampo and Ashley, 1999; Deocampo, 2005).

Hominin Population of the Guadix-Baza Depression

The area emerged in the Guadix-Baza Depression (2,925 km^2) allows calculating the population size of *Homo* sp. that could inhabit it. As noted earlier, the estimate of hominin population density for BL and FN-3 is 0.12 individuals per km^2 considering a scavenging behavior as the optimal scenario for the procurement of ungulate carcasses (Rodríguez-Gómez et al., 2016a). This translates in a population size of $\sim$350 individuals, which would result in 7–12 hominin groups based on the estimates of mean local group size for modern hunter-gatherers (Binford, 1980; Marlowe, 2005). If we choose for a strict hunting behavior, which implies that the hominins had not access to the largest prey size classes, the population density would be 0.095 individuals per km^2 (Rodríguez-Gómez et al., 2016a). This would result in a population of $\sim$280 individuals distributed among 5–9 foraging groups. Both estimates are very low and clearly below the minimum viable population size for mammals (including primates), which has been estimated in 3,876 individuals, with a 95% confidence interval of 2,261–5,095 individuals (Traill et al., 2007). This suggests that although the prey biomass estimated in the Guadix-Baza was similar or even higher than in many modern African ecosystems, the viability of the hominin population that inhabited the sedimentary basin could be compromised due to random oscillations in population size such as those resulting from fluctuations in resource availability and epidemics. This could eventually lead to bottlenecks, genetic drift, inbreeding depression, and local extinction.

A skull of the hypercarnivorous wild dog *Lycaon lycaonoides* (specimen VM-7000) provides evidence of inbreeding depression in the local population of this species. The skull preserves the cranium and mandible in anatomical connection and corresponds to a relatively old individual with moderately worn permanent dentition (Palmqvist et al., 1999). It displays a high degree of cranial fluctuating asymmetry (FA), which is especially marked in the frontal region, and shows dental anomalies, including agenesia of several teeth like the upper right canine (Bartolini-Lucenti et al., 2021). The incidence of FA in a population must be tested at the population level and not based on a single individual (Palmqvist et al., 1999). However, the fossil record of *L. lycaonoides* is scarce in Guadix-Baza (a few specimens from VM, see details in Palmqvist et al., 2022b) and VM-7000 is the only complete skull. This limitation on sample size precludes the hypothetico-deductive method and forces to use the 'abductive research method,' which means that the best explanation at hand for interpreting the anomalies of VM-7000 is to consider that they evidence FA resulting from developmental instabilities caused by inbreeding depression (Palmqvist et al., 1999; Bartolini-Lucenti et al., 2021).

Fluctuating asymmetry results from small, random accidents during ontogeny in morphological traits that would otherwise appear as bilaterally symmetric. These perturbations can also emerge from developmental stress (e.g., induced by parasitic infection), but their incidence in a population uses to correlate with the level of genetic inbreeding, which increases the homozygosity of enzyme polymorphisms and results in developmental instabilities (Wayne et al., 1986; Palmqvist et al., 1999; Leamy and Klingenberg, 2005). Inbreeding increasingly becomes a serious threat to local wildlife populations as habitats shrink and fragment (Spiering et al., 2011). This results in bottlenecks and changes in metapopulation structure, which translate in a quite small effective population size and lead to the loss of genetic diversity and inbreeding depression, as documented in the cheetah (Wayne et al., 1986; Menotti-Raymond and O'Brien, 1993; Hedrick, 1996; however, see also Merola (2011)). The expression of the deleterious effects of increased homozygosity and their consequences for individual fitness have been shown in canids (Ellegren, 1999; Fitzpatrick and Evans, 2009; Spiering et al., 2011). Anodontia and cranial asymmetry are documented in small populations of wolves subject to bottlenecks and inbreeding, as happens in Białowieża Forest (Buchalczyk et al., 1981; Vilà et al., 1993). Edwards et al. (2013) showed an increase in fluctuating asymmetry in museum skulls of African painted dogs that span a period of a hundred years, which parallels the decline in the populations of the species in sub-Saharan Africa during the last century. This suggests that the malformations of the fossil skull of VM would reflect developmental instabilities resulting from a high level of genetic homozygosity in the small population of wild dogs that inhabited Guadix-Baza during Early Pleistocene times. Specifically, the population density of *L. lycaonoides* expected for optimal ecological conditions, calculated using the equation of Damuth (1993) for African flesh-eaters in open environments, is 0.23 individuals per km^2 (Rodríguez-Gómez et al., 2017a). However, the value of sustainable density for this predator in VM is lower, 0.13 ind./km^2, which translates in a population of only 380 individuals (i.e., like the one estimated for the hominins). Moreover, the effective population size of modern painted dogs is typically reduced to 20–35% of the censused population by reproductive suppression of subordinates and uneven sex ratios (Creel and Creel, 1998). In the case of VM, this would result in an effective population size for *L. lycaonoides* of around one hundred individuals, which would have promoted further inbreeding. However, the dog from VM was able to reach adulthood, as shown by its moderately worn permanent dentition, despite severe developmental handicaps, which suggests that cooperative

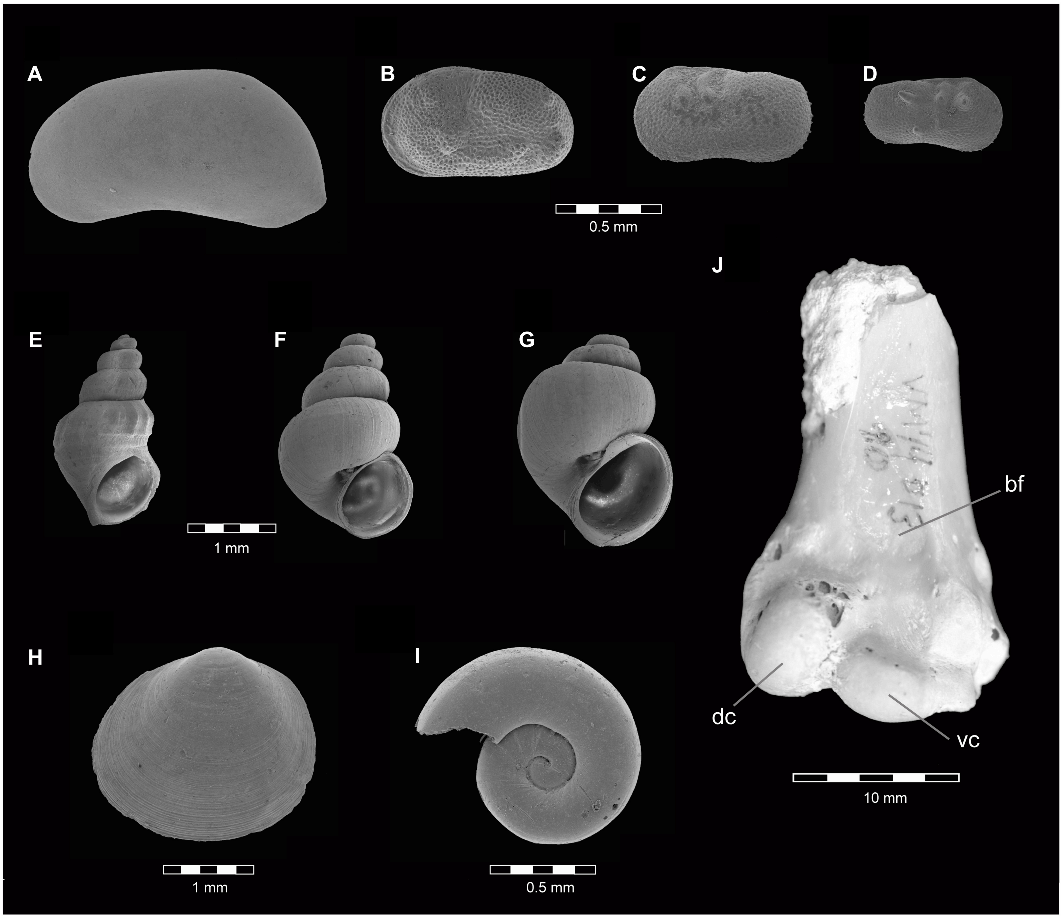

FIGURE 8 | Ostracods, mollusks and avian remains identified in the Late Villafranchian archeological sites of Barranco León (BL) and Fuente Nueva 3 (FN3) in Orce (Guadix-Baza Depression, SE Spain). Scanning electron microscope photographs of ostracod **(A–D)** and mollusk **(E–I)** shells. **(A)** *Candona* sp. **(B)** *Cyprideis torosa.* **(C)** *Ilyocypris bradyi.* **(D)** *Ilyocypris gibba.* **(E)** *Melanoides tuberculate.* **(F)** *Hydrobia* aff. *acuta.* **(G)** *Bithynia tentaculate.* **(H)** *Pisidium casertanum.* **(I)** *Gyraulus* cf. *laevis*. **(J)** Distal humeral portion of an aquatic bird from Venta Micena (specimen VM-D13-10) in cranial view, which has been tentatively attributed to a Common Shelduck (*Tadorna tadorna*), bf-brachial fossa, dc-dorsal condyle, vc-ventral condyle.

behavior from other members of the hunting pack may have helped it to survive (Palmqvist et al., 1999; Bartolini-Lucenti et al., 2021). Similarly, cooperation among hominins has been reported in Dmanisi. This site documents the earliest human presence out of Africa (~1.8 Ma) and preserves a human skull that lost all but one of its teeth several years before the time of death (composite skull D 3444/D 3900), as evidenced by extensive bone loss due to resorption of the alveolar processes. Although the etiology of the absence of teeth differs from that described in the wild dog of VM, the survival of this edentulous individual probably relied also on the assistance (e.g., food chewing) from other members of the group (Lordkipanidze et al., 2005, Lordkipanidze et al., 2006).

The high level of genetic homozygosis deduced for the population of *L. lycaonoides* that inhabited Guadix-Baza — conditions that would presumably apply also to the hominin population— can be explained as resulting from its small size, as this population was geographically isolated from other similar ecosystems in the surrounding areas (Palmqvist et al., 1999). Interestingly, the lion population that inhabits the Ngorongoro Crater depicts a similar situation: these lions form a small, naturally isolated population of 75–125 individuals, which has been historically subject to severe bottlenecks followed by limited recolonization by lions from the nearby Serengeti ecosystem. This has resulted in high levels of inbreeding and lack of genetic variability in the contemporary Crater lion population compared to the much larger Serengeti population, which correlates with increased levels of sperm abnormality and decreased reproductive performance (Packer et al., 1991).

Any discussion on the level of genetic variability of the population of early *Homo* that inhabited Guadix-Baza makes it necessary to consider the levels of inbreeding depression withstood by modern hunter-gatherers. Genealogical information showed evidence of inbreeding in 165 out of 931 (~18%) individuals of the Hadza population (Stevens et al., 1977). Similarly, the !Kung, Khwe and African Pygmies exhibit low genetic diversity coupled with high frequencies of divergent mtDNA haplotypes not found in the surrounding agricultural groups, which suggests small population sizes and long-term

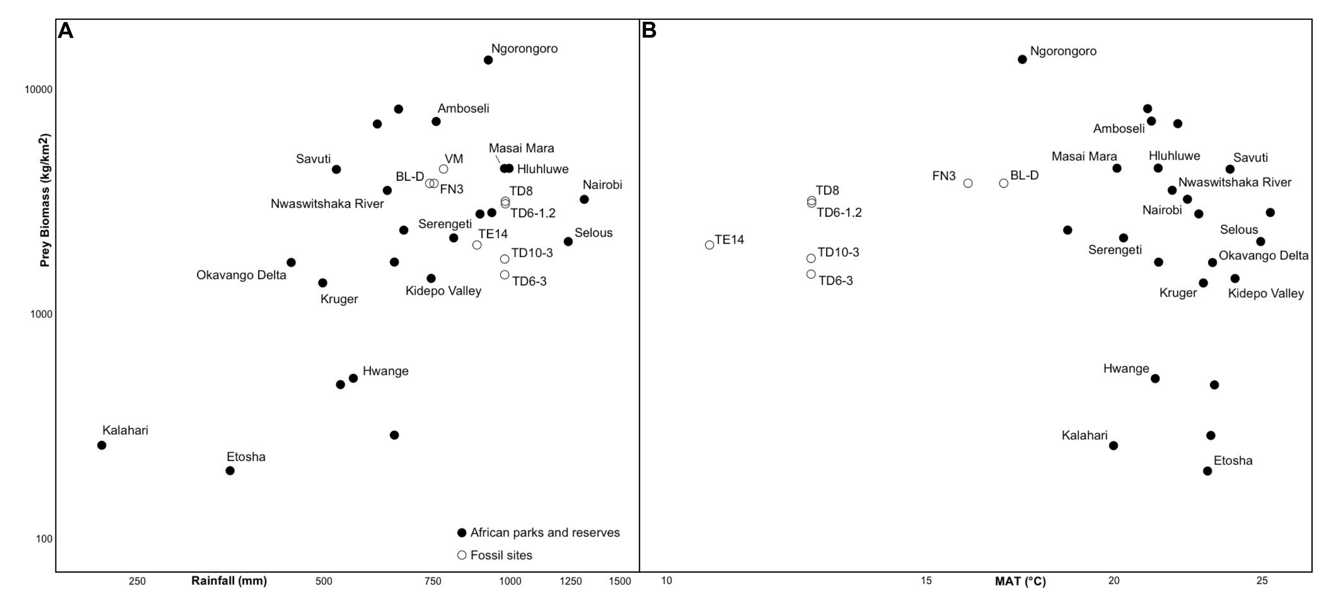

FIGURE 9 | (A) Scatter plot of prey biomass (in kg/km^2) and annual rainfall (in mm). **(B)** Scatter plot of prey biomass and mean annual temperature (MAT, in °C). The points correspond to 23 African Natural Parks and Game Reserves [data on prey biomass compiled by Hatton et al. (2015) from several sources; data on rainfall and MAT from Fick and Hijmans (2017)] and the paleontological sites of Atapuerca and Orce discussed in the text. The estimates on rainfall and MAT are from Blain et al. (2011a,b, 2016), García-Aguilar et al. (2014), and Rodríguez et al. (2014). Prey biomass values for the fossil assemblages were obtained using the Weibull model (see details in Martín-González et al. (2019)). TD, Trinchera Dolina, Atapuerca (NW Spain). TE, Sima del Elefante, Atapuerca. BL-D, Barranco León (Level D), Orce (Guadix-Baza Depression, SE Spain). FN3, Fuente Nueva 3, Orce. VM, Venta Micena, Orce. Scatter plots produced with software SPSS v. 25.

isolation, respectively (Vigilant et al., 1991; Chen et al., 2000; Oota et al., 2005). Moreover, Trinkaus (2018) showed an unexpectedly high frequency of abnormalities in the fossil record of Pleistocene *Homo,* including from minor but rare dental, vertebral, and carpal variants to exceptional systemic disorders. This suggests ubiquitous stress among the Pleistocene foragers and/or high levels of consanguinity.

Although the hominin population of Guadix-Baza was probably small, it would not remain in strict isolation: there are several connecting corridors in the mountainous reliefs that surround the basin (see arrows in **Figure 7**). Moreover, some species ecologically and climatically constrained like the hippo probably dispersed by these corridors from the coastal environments, which led to their colonization of the lacustrine environments of this endorheic basin. In the case of the hominins, the corridors would result in some gene flow with other populations from adjacent areas, although the amount of gene introgression was probably limited, as happens in modern hunter-gatherers. Moreover, data from Binford (1980: **Table 1**) for Equatorial and Subequatorial populations of non-equestrian hunters-gatherers provide a mean number of 24.8 residential moves per group and year, a mean distance of 15.3 km between sites and a mean total circuit distance covered annually of 310.6 km. This suggests that each of the few hominin groups that inhabited the Guadix-Baza Depression would travel each year searching for food a linear distance that would cover the entire basin. These changes in residential moves would presumably follow a random motion, as happens in the case of modern hunter-gatherers (Brown et al., 2007; Raichlen et al., 2014). For this reason, the probability of intersecting one of the five connecting corridors of the basin perimeter (**Figure 7**) in any of these foraging random walks would be low, resulting in a limited amount of gene flow with the surrounding populations and long-term isolation.

According to these data, Guadix-Baza was home for a small hominin population during the late Early Pleistocene, which viability in the medium and long term could be compromised by population bottlenecks and inbreeding depression. This explains the sporadic and discontinuous nature of the archeological record in the sedimentary basin. Although such situation cannot be extrapolated to the whole European record of hominin presence for these ancient chronologies, the scarcity of Early Pleistocene archeological sites points to intermittent dispersal events, which probably reflects hominin incursions that failed to establish a more permanent character (Dennell, 2003; MacDonald et al., 2012).

However, we must introduce here a cautionary note: Flores Island, which has an area of 13,540 km^2 (i.e., ~4.6 times the living area of the Guadix-Baza Depression), has a record of hominin presence since ~0.7 Ma (van den Bergh et al., 2009, 2016). The island allowed the survival of a local population of *H. erectus* during more than half a million years and this happened without any evidence of external gene flow having been detected so far. In their adaptation to the insular environment, these hominins evolved in a short time to a dwarfed form, *H. floresiensis,* which represents a striking case of evolutionary reversal in the trend of body and brain size increase in *Homo* (van den Bergh et al., 2016). This was facilitated by the relatively small size of the population, although the energy expenditure of the small-bodied *H. floresiensis* could be half that of *H. erectus* (Dennell et al., 2014), which probably resulted in a higher population density. Unlike other hominins, *H. floresiensis* shows a combination of primitive traits in the canine and premolar teeth, which are comparable to those of Early Pleistocene *H. erectus,* together with a molar morphology more progressive than in modern humans (Kaifu et al., 2015). These features make sense in the context of a highly isolated inbred population with small genetic variation (as expected from the founder effect of the island colonizers), a population that was adaptively constrained. It should be noted, however, that a similar combination of primitive and modern characters is also present in *H. luzonensis,* the dwarfed hominin of the larger island of Luzon (Philippines), which probably descended also from an initial population of *H. erectus* (Détroit et al., 2019).

Continuity or Discontinuity in the Earliest Hominin Settlements of Europe?

During the last decades, the discovery of a significant number of Early Pleistocene sites that preserve evidence of hominin presence in Western Europe has renewed the debate on: (i) the chronology of the oldest dispersal of *Homo* out of Africa; (ii) the success of these ancient populations in the colonization of the European landscapes; and (iii) their continuity or discontinuity (Arribas and Palmqvist, 1999; Roebroeks, 2001; Dennell, 2003; MacDonald et al., 2012; Bermúdez de Castro et al., 2013; Rodríguez-Gómez et al., 2014a, 2016a, 2017a,b,c). Although Dmanisi provides conclusive evidence on the presence of hominins at the gates of Europe by ∼1.8 Ma (García et al., 2010), the overall evidence of hominin settlements in North Africa and Europe is scarce before the Middle Pleistocene and is basically restricted to the circum-Mediterranean realm (Rodríguez-Gómez et al., 2016a, 2017a; Butynski, 1982; Capaldo, 1997; Roebroeks et al., 2018). Muttoni et al. (2010, 2013) proposed that the first occurrence of *Homo* sp. in Southern Europe took place between the Jaramillo subchron and the Brunhes-Matuyama boundary (i.e., in the 0.99–0.78 Ma interval), a time window that encompasses the latest Early Pleistocene global climate transition centered on MIS 22 at ∼0.9 Ma, the first prominent cold stage of the Pleistocene. Under this view, hominin presence in Southern Europe would have been ephemeral from ∼1 Ma onward, with occasional short northward expansions along the western coastal areas when temperate conditions allowed it (Roebroeks, 2001; Muttoni et al., 2010). In contrast, Leroy et al. (2011) argued that there were up to 42 possible narrow windows of 41 ka for hominin dispersal in Europe through the Early Pleistocene (2.58–0.78 Ma). In their model of climate and vegetation change, these windows coincided with transitions from glacial to interglacial cycles forced by obliquity, which resulted in the opening of the landscapes with the appearance of grasslands and forested steppes like those of Orce (Mendoza et al., 2005; Saarinen et al., 2021). This landscape was similar to the recent reconstruction of Dmanisi as an open wooded savannah and grassland by Bartolini-Lucenti et al. (2022). Leroy et al. (2011) considered that the presence of hominins was not possible during the full glacial periods, which would be too cold for them, and neither in the transitions from interglacial to glacial cycles, when the landscapes were densely forested. In any case, the oldest conclusive evidence of human presence in Western Europe is found at BL and FN3 in Orce (∼1.4 Ma) and TE9 level (∼1.2 Ma) in Atapuerca (see review in Palmqvist et al., 2016). In addition, the carnivore guild of VM, a site ∼200 ka older than BL and FN3 that shows no evidence of hominin presence, has a lower level of competition intensity for meat than in the case of BL and FN3 (Rodríguez-Gómez et al., 2016a, 2017a). This suggests that the delay of ∼0.4 Ma between hominin arrival in the Caucasus and Western Europe was not a matter of ecological opportunity and other factors (climatic or geographic barriers to dispersal) played a role here (Rodríguez-Gómez et al., 2017a).

The scarcity of Early Pleistocene archeological sites in Europe indicates that the colonizing capabilities of early *Homo* outside Africa may have been overestimated, as the dispersals were not automatically followed by permanent settlements (Dennell, 2003). Further fieldwork will undoubtedly fill many gaps in the Early Pleistocene hominin record of Europe, but current evidence is consistent with the view that: (i) the oldest populations outside East Africa were spatially and temporally discontinuous; (ii) hominin expansion was strongly constrained by latitude; and (iii) the occupation of temperate regions north of latitude 40° was largely confined to interglacial periods (Dennell, 2003; Leroy et al., 2011; Rodríguez et al., 2011, 2013; MacDonald et al., 2012; Bermúdez de Castro et al., 2013). However, continuity of hominin settlements in the refuge areas of Southern Europe during the cold periods of the Early Pleistocene cannot be discarded: the presence of hominins at Atapuerca during long time periods suggests that they were well-adapted to the hard and seasonal conditions of the northern hemisphere at a latitude of 42° and an altitude of 1000 m (Bermúdez de Castro et al., 2013). Climate conditions in Guadix-Baza were milder than those of Atapuerca (**Figure 9**), with the presence of open plains with woodland patches and water-edge areas (Mendoza et al., 2005; Saarinen et al., 2021). This difference between the North and South of the Iberian Peninsula is also seen today (Blain et al., 2009, 2011a,b). Moreover, the thermal springs of Guadix-Baza resulted in a milder and more productive environment in the lacustrine systems of the basin compared to present-day conditions (García-Aguilar et al., 2014, 2015). Therefore, the information available suggests continuity for the human settlements in the Iberian Peninsula during a period of at least 300 ka before the Jaramillo subchron (Agustí et al., 2009; Bermúdez de Castro et al., 2013). According to Agustí et al. (2009), after this phase the hominins would disappear from Western Europe during a long period that included part of the Jaramillo subchron and until MIS 22 (0.88–0.87 Ma). This would be caused by an extreme decrease in mean annual temperature and an increase in mean annual precipitation, as deduced from the herpetofauna (Agustí et al., 2009). However, geochronological and paleomagnetic data for levels of Trinchera Dolina of Atapuerca indicate a continued presence of hominins in northern Spain during the time interval of ∼1.0–0.3 Ma (Bermúdez de Castro et al., 2013).

The archeological record of Sima del Elefante and Gran Dolina cave sites in Atapuerca, which preserves relatively continuous stratigraphic sequences that stretch back from ∼1.2 Ma to the Matuyama/Brunhes boundary, suggests that the Iberian Peninsula was occupied by at least two different hominin populations (Bermúdez de Castro et al., 2013). The human remains from level TD6 of Gran Dolina, dated to 0.97–0.79 Ma by a combination of biochronology, magnetostratigraphy and geochronology (Duval et al., 2018; Parés et al., 2018), have been ascribed to *Homo antecessor,* a species considered to represent the most recent common ancestor of Denisovans, Neandertals and modern humans, or at least very close to the cladogenetic event that preceded the divergence of these species (Bermúdez de Castro et al., 2017; Welker et al., 2020). The dental proteome of *H. antecessor* indicates that it represents a close sister lineage to subsequent Middle and Late Pleistocene hominins (Welker et al., 2020). In Sima del Elefante, the few fossils from TE9 do not allow to conclude if *H. antecessor* has deep roots in the Early Pleistocene before the Jaramillo subchron (Bermúdez de Castro et al., 2013, 2017). The hominin population of TE could be different from that recorded at TD6, but the evidence recovered is too scanty to make a strong claim. What seems clear is that the hominins never disappeared from the Atapuerca habitats, as the archeological record at the base of TD4 is of ∼1.0 Ma (Carbonell and Rodríguez, 1994). This argues for the continuity of the hominin settlements in the circum-Mediterranean realm, even if we admit the possibility of discontinuity by the local substitution of the original population, its assimilation or crossbreeding.

Finally, Bermúdez de Castro and Martinón-Torres (2013) hypothesized the existence of a "source population" of hominins in a central area of dispersal, which they tentatively located in the Levantine Corridor. When climatic and ecological conditions were favorable, hominins would colonize from this area the Eastern and Western territories of Eurasia. Following Carrión et al. (2011); Bermúdez de Castro and Martinón-Torres (2013) considered that the key for activating evolutionary change in this hominin population would be the geological instabilities that resulted in an increase in physiographical heterogeneity, biodiversity and ecological interaction. The latter conditions were boosted in the Guadix-Baza Depression by the abundance of thermal springs linked to intense tectonic activity, which was a major determinant in the establishment of biodiversity "hot spots" with high biological productivity (García-Aguilar et al., 2014, 2015; Rodríguez-Gómez et al., 2016a, 2017a, 2022; Palmqvist et al., 2022a).

CONCLUSION

Evidence of anthropogenic action from the archeological levels of BL and FN-3 indicates that the hominin population that inhabited the Guadix-Baza Depression during Early Pleistocene times exploited the prey carcasses left abandoned by saber-tooths, which suggests a subsistence strategy based on passive scavenging rather than on active hunting for obtaining meat, fat, and bone marrow. In addition, other animals of small size available in the environment, including rodents, leporids, tortoises and birds, were also presumably consumed, together with eggs, invertebrates, honey, and a wide spectrum of edible vegetation. The population size estimated for the hominins of the basin was low, ∼350–280 individuals distributed in five to twelve groups of hunter-gatherers. This probably compromised the long-term viability of the population due to the effects of bottlenecks and inbreeding depression, as detected in the coeval population of wild dogs, which probably led them to extinction and helps to explain the scarcity and discontinuous nature of the archeological record in the basin.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

PP wrote the manuscript and all co-authors made contributions. SR-M, BM-N, and PP prepared **Figure 1**. AG-M, JMG-A, AG, and SR-M prepared **Figure 2**. BF prepared **Figure 3**. GR-G prepared **Figure 4**. PP and MPE prepared **Figures 5**, **6**. AG-M and JMG-A prepared **Figure 7**. AG and FS prepared **Figure 8**. GR-G and PP prepared **Figure 9**. BM-N, MPE, and SR-M prepared **Table 1**. All authors contributed to the article and approved the submitted version.

FUNDING

This work was supported by four projects from the Spanish Ministry of Science, Innovation and University (Grant Nos. CGL-2016-78577-P, CGL-2016-80975-P, PGC2018-093925-B-C31, and PID2019-111185GB-I00), by two projects from Junta de Andalucía (Grant Nos. UMA18-FEDERJA-18 and P18-FR-3193), by one project from Generalitat de Catalunya (Grant No. GENCAT 2017SGR 859), and by Research Group RNM-146 from Junta de Andalucía.

ACKNOWLEDGMENTS

GR-G was funded by the program IdEx Bordeaux "Investments for the future," financed by L'Agence Nationale de la Recherche of France (ref. ANR No.-10-IDEX-03-02) with the project *Analysis of Kozarnika food webs and comparison with other Pleistocene sites of Western Europe.* The Program Juan de la Cierva of the Spanish Ministry of Science, Innovation and University funded GR-G (FJCI-2016-28652) and FS (IJCI-2017-32116). GR-G is supported by an "Atracción de Talento" postdoctoral contract (2019-T2/HUM-13370) from the Comunidad de Madrid and Universidad Complutense de Madrid (Spain). FS is supported by a postdoctoral fellowship of Junta de Andalucía. Last but not least, we gratefully acknowledge the insightful comments and helpful criticism from two reviewers and also from the editor, MA.

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frontiers | Frontiers in Earth Science

ORIGINAL RESEARCH
published: 23 May 2022
doi: 10.3389/feart.2022.893776

The Significance of Subtlety: Contrasting Lithic Raw Materials Procurement and Use Patterns at the Oldowan Sites of Barranco León and Fuente Nueva 3 (Orce, Andalusia, Spain)

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Specialty section:
This article was submitted to Quaternary Science, Geomorphology and Paleoenvironment, a section of the journal Frontiers in Earth Science

Received: *10 March 2022*
Accepted: *19 April 2022*
Published: *23 May 2022*

Citation:
Barsky D, Titton S, Sala-Ramos R, Bargalló A, Grégoire S, Saos T, Serrano-Ramos A, Oms O, Solano García J-A, Toro-Moyano I and Jiménez-Arenas JM (2022) The Significance of Subtlety: Contrasting Lithic Raw Materials Procurement and Use Patterns at the Oldowan Sites of Barranco León and Fuente Nueva 3 (Orce, Andalusia, Spain). Front. Earth Sci. 10:893776. doi: 10.3389/feart.2022.893776

Situated in southern Spain's Guadix-Baza basin, Barranco León and Fuente Nueva 3 (Orce, Andalusia, Spain) are two of the most important western European Oldowan archeological sites. After 30 years of quasi-uninterrupted excavations, these two occurrences have yielded exceptional lithic and faunal records in precisely dated stratigraphic situations, providing a wealth of information about the oldest presence of hominins outside of Africa (1.4 and 1.3 Ma, respectively). Recently, excavations and multidisciplinary research have allowed to discern new patterns of lithic raw material procurement and use patterns practiced by the Orce hominins that enable us to clearly distinguish different behavioral schemes between these two sites; in spite of their spatial proximity. This paper explores new data from the lithic collections in relation to hominin technical and economic behavior, highlighting subtle but significant differences in their exploitation of local limestone and flint clasts more than a million years ago. During this period of the late Early Pleistocene, these sites were situated on the shores of an ancient saline lake and fresh water sources were available. This favorable environmental situation, while attractive to the hominins, also supported life for an abundance of large mammals, including competitive large carnivores, underlining questions of expedience as an influence on techno-morphology in these early stone toolkits. This paper analyzes these themes, highlighting updated information from these and other key European late Early Pleistocene sites.

Keywords: Orce, lithic raw materials, technology, stone tools, hominin behavior, Oldowan

1 INTRODUCTION

The Oldowan sites of Barranco León (BL) and Fuente Nueva 3 (FN3) are located in the Guadix-Baza depression near the town of Orce (Spain). Placed at an altitude of ~1,000 m. a.s.l. and only 4 Km apart from one other, these unique Oldowan occurrences have been the object of excavations and archeological research since the early 1990s. While in the past these sites, dated respectively to 1.4 and 1.2 Ma, have commonly been confounded into the single referent 'Orce', they constitute distinct depositional contexts composed of multiple layers containing archeo-paleontological materials. It is precisely these subtle but significant differences in environmental conditions and site formation processes that we present here as revelatory of behavioral shifts in lithic raw material's sourcing and use by their hominin dwellers. This paper focuses on intra and inter-site specificities to compare behavioral patterns relative to lithic raw material's gathering, exploitation, use and discard. In spite of the paucity of information from the European human fossil record dating to this period, this special focus unites all of the data obtained up to now from both lithic assemblages to reveal information about the social and cognitive practices of the first human populations present in Europe. As is in other Oldowan lithic assemblages, the hominins present at Orce well-over a million years ago exploited local raw materials collected from around the sites and even within the depositional sequences themselves (Barsky et al., 2015a; Titton et al., 2021). At BL and FN3, limestone cobbles and blocks, as well as flint nodules, were picked up, transported and used by the hominins, generally from detritus erodes from the Jurassic formations around the sites. In spite of this local raw material procurement strategy, interesting patterns of exploitation and use are identifiable as factors that contribute significantly to our understanding of selective behaviors and preferences in raw material uses that differ in subtle but significant ways between the two archeological occurrences.

To better understand hominin behavioral aspects in terms of lithic raw materials, we begin by providing a synthesis of the geo-archeological contexts of BL and FN3, highlighting new information about their specific climatic, environmental and depositional features, before more closely examining their role as potential conditioning factors. This in turn raises interesting issues about the role of technology in overcoming natural constraints and thus becomes highly revelatory of hominin cognitive processes in dealing with the specific landscape circumstances that may have been dictating these behaviors. In the case of BL and FN3, this type of analysis takes on special significance because it allows to build up a discussion about how technological conducts played a role as a favoring aspect, finally enabling early hominin groups to successfully and durably implant themselves in western Europe. In recent years, our research has deeply explored the dichotomous use patterns displayed by the Orce hominins in their exploitation of limestone and flint, with the former showing especially high morpho-techno-variability (Carbonell et al., 2009), in particular relating to an unprecedented range of percussive activities (Barsky et al., 2015b; Barsky et al., 2018; Titton et al., 2018). The limestone assemblages contain flakes, cores, and chopper and percussive-type tools, while the flint reflects only the production of small-sized flakes. Despite seeming stability, we find remarkable differences in the operative permanency between the sites. The BL and FN3 toolkits now comprise a total of 3,925 flint and limestone pieces (BL = 2,434 pieces; excavations 1995–2018 and FN3 = 1,491 pieces, excavations 1995–2017) (**Table 1**), currently making them one of the best references for understanding the specificities of the 'European Oldowan' (Titton et al., 2020). In addition to the lithics, both sites have yielded rich assemblages of mega, large and medium to small-sized mammals (faunal remains: BL = 34,045 and FN3 = 22,623, after new inventory (Junta de Andalusia, Museum of Ethnography and Archeology of Granada), as well as rich collections of micro fauna that, supported by radiometric dating, contribute to our growing knowledge about the biochronology and climatic/environmental settings (detailed below with references). As a final step, we apply here the behavioral templates provided by the Orce contexts to perform a comparative analysis synthesizing what is known about raw material exploitation in other European Oldowan sites.

2 THE BARRANCO LEÓN AND FUENTE NUEVA 3 SITES: ENVIRONMENTS AND CONTEXTS

2.1 Geographical Context and Discoveries of the Barranco León and FN3 Sites

The Guadix-Baza basin (GBB) spans a large surface area of the southeastern sector of the Iberian Peninsula (4,500 km^2) at the contact between the Internal Zones (mainly built up of Paleozoic basement rocks) and the External Zones (mainly built up of Mesozoic carbonate cover rocks, **Figure 1**). This intramontane basin is well-known to geologists who have explored the different layers of its thick and continuous depositional sequences since the 1970s (Vera, 1970; Vera et al., 1985; Soria et al., 1987; Hüsing et al., 2010; Oms et al., 1998; Oms et al., 2000a; Oms et al., 2016). The GBB encloses a unique continental Plio-Pleistocene and Holocene record from the Late Turolian and Middle to Late Pleistocene (Soria et al., 1998) that is characterized by two main depositional contexts: 1) the western Guadix sector of the basin, characterized fluvial sedimentation and 2) the mostly lacustrine eastern Baza sector, which hosts the Orce sites of BL and FN3 (Oms et al., 1998). The salient geographical feature of the Baza sub-basin was the prolonged existence (~5 million years) of a saline lake, bounded to the north by the External Zone (Sierras de Cazorla, Maria and Umbría) and to the south by the by the Sierra Nevada. The extension and morphology of the lake varied through time with the vicissitudes of changing climatic and tectonic contexts that also affected freshwater inputs to the system, originating both from the surrounding mountain ranges and from underground perennial sources; some of which are still active today (Oms et al., 2016) (**Figure 1D**). The Baza Formation is subdivided into three members: the Lower Member is calcareous (composed of shallow lacustrine

TABLE 1 | Distribution of the different kinds of tools composing the lithic assemblages of the Barranco León (1995–2018) and Fuente Nueva 3 (1995–2017) sites in accordance to the two main raw materials. Note in Barranco León that there are 15 items that have been preliminarily attributed with different raw material determinations that have yet to be explored in detail: 6 non-modified clasts, 1 knapped/shaped item, 3 flakes, fragmented flakes and flake fragments and 5 debris. In Fuente Nueva 3 there are 17 items that have been preliminarily attributed with a different raw material: 2 non-modified clasts, 1 knapped/shaped item; 10 flakes, fragmented flakes and flake fragments and 5 debris.

Tool Category	Barranco León		Fuente Nueva 3	
	N	%	N	%
Limestone non-modified clast	231 +51 hammerstones	34.6	78 +48 hammerstones	15.2
Limestone knapped/shaped (macro)	87	10.7	99	12.0
Limestone whole and broken flakes	130	15.9	253	30.6
Limestone debris	317	38.8	349	42.2
Total limestone	**816**	**100%**	**827**	**100%**
Flint non-modified (macro)	1+ 57 small pebbles	3.6	1	0.2
Flint knapped	55	3.4	30	4.5
Flint whole and broken flakes	729	45.0	524	78.9
Flint debris	776	48.0	109	16.4
Total flint	**1,618**	**100%**	**664**	**100%**
Total assemblage	**2,434**	**Limestone= 33,5% Flint= 66,5%**	**1,491**	**Limestone= 55,5% Flint= 44,5%**

Bold letters in table indicate totals.

limestone); the Middle Member is composed of detrital materials including reddish alluvial clays, sandstones, marshy clays and limestone and the Upper Member (comprising the two Oldowan sites) is an accumulation of lacustrine limestones, calcareous silts, dark clays, sands and locally formed gypsum (Vera et al., 1985; Soria et al., 1987; Oms et al., 2000a; Oms et al., 2000b; Oms et al., 2011).

The fluctuations of the lake's extension and depth generated marginal lacustrine and palustrine settings that permitted the accumulation and preservation BL and FN3 sites (**Figure 2**). Basin infill lead to the drying of the lake in the Middle Pleistocene and towards the end of the Pleistocene, it became part of the Guadalquivir River catchment. Thus, the basin started to be an exoreic system that at some places is leaving sedimentary successions of over 100 m encompassing hundreds of thousands of years. Erosive forces are opening up huge ravines and are lending the region its almost 'lunar' aspect. The enormous sedimentary sections thus exposed offer particularly advantageous circumstances for geo-archeological investigations, while also providing ideal conditions for the digging-out of cave homes for troglodyte dwellings (*casas cuevas*) linked to the rebellion and expulsion of the "moriscos" (Hispanic-Arab population converted to Christianism) in the XVI century (Asenjo Sedano, 1972; Urdiales Viedma, 2003). In 1976, surveys undertaken in the Baza sector of the GBB led to the discovery of Venta Micena; a vast paleontological site devoid of any human presence that predates BL and FN3 by some 200 Ka (*ca*. 1.6 Ma, Duval et al., 2011; Agustí et al., 2010a; Agustí et al., 2015a). The VM4 site, site has recently been shown to consist of two distinct layers corresponding to separate depositional events (Luzón et al., 2021). The site was formed by freshwater inputs above the water table of the nearby saline Baza lake (Granados et al., 2021). Recent publications have shown that climate could have been a key limiting factor for the arrival/installation of hominins some 200 thousand years later (at BL and FN3), following the establishment of a somewhat more clement climatic situation in this area (Blain et al., 2011, 2016; Sánchez-Bandera et al., 2020; Saarinen et al., 2021). In 1983, surveying in the region of Orce led to the discovery of BL, which was initially recognized as a paleontological site (Vera et al., 1985), until 1994, when the first lithics were found (Gibert et al., 1992; Gibert et al., 1998). In 1991, the first flint tools were discovered at the nearby site of FN3 (only 4 Km away from BL) by a local inhabitant and, in 1992, more archeological materials were unearthed during the installation of a telephone pole, leading to the undertaking of the first test excavations (Tixier et al., 1995; Turq et al., 1996; Martínez-Navarro et al., 1997; Gibert et al., 1998).

2.2 Stratigraphy and Dating of the Barranco León and FN3 Sites

Over years of excavations and research, the BL and FN3 sites have been analyzed using a multidisciplinary approach that has enabled to chrono-stratigraphically categorize both depositional and occupational contexts. Indeed, the full lateral extension of these open-air Oldowan sites remains unknown and their discovery has been contingent to findings made fortuitously, basically during surveys in the region. Doubtlessly, these occurrences constitute auspicious finds, where a hominin presence has been registered in water-rich environments favorable to all forms of life. Hominins were present around the Baza lake area, moving through the landscape amongst the numerous other mammal species occupying the zone and taking advantage of favorable and life-promoting conditions. Indeed, apart from the hominin presence that is clearly registered (as stated above) by the very numerous Oldowan stone tools (Toro-Moyano et al., 2010,

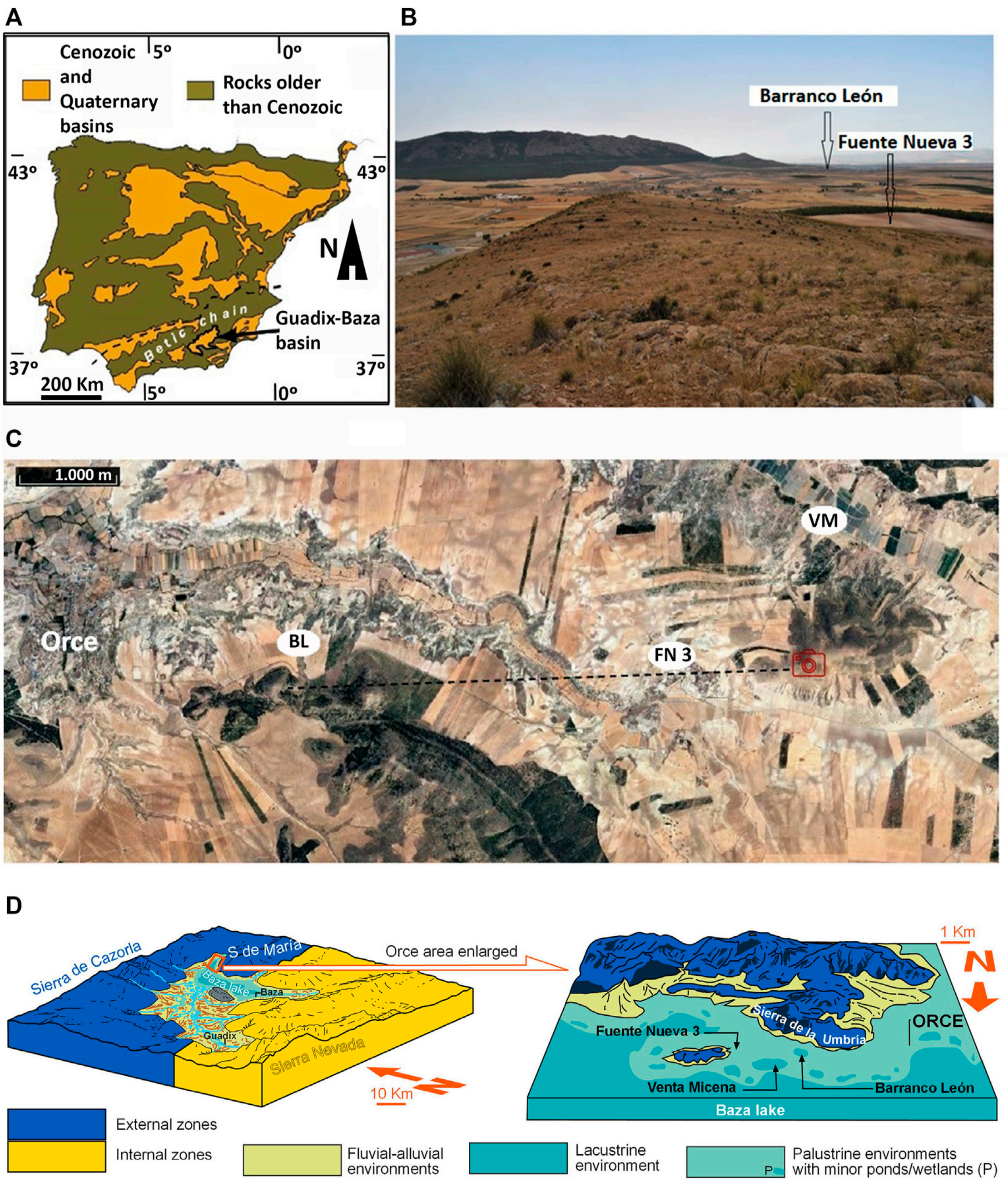

FIGURE 1 | (A) Location of the Guadix-Baza Basin in Spain (image inset) **(B)** Location of Barranco León and Fuente Nueva 3 with respect to the slope of the Sierra Umbría (Photo: S. Titton) **(C)** Satellite view showing the location of the BL and FN 3 in relation to the village of Orce (Image from Google Earth, Titton, 2021). Site locations and photograph **(B)** Capture situation facing BL from the promontory of the Cañada del Campo near FN 3 **(D)** Geological block diagrams illustrating the context and positioning of the Venta Micena paleontological site and the Oldowan sites of BL and FN 3 in relation to the fluctuating shoreline of the Baza paleo lake (adapted after Oms et al., 2016).

Moyano et al., 2011); both of the sites have yielded a wide range of herbivores and carnivores with little differences observed in species' relative representation between the two sites (e.g., Martínez-Navarro et al., 2010; Ros-Montoya et al., 2021; Saarinen et al., 2021). Meanwhile, biochronology and climatic features for each site have been refined thanks to numerous and ongoing studies of the relatively abundant micro-vertebrate assemblages that include micro-mammals and herpetofauna (Blain, 2005; Blain, 2009; Agustí et al., 2010a; Agustí et al., 2010b; Bailon, 2010; Blain and Bailon, 2010; Furió, 2010; Blain et al., 2011; Lozano-Fernández et al., 2015; Agustí et al., 2015a; Blain et al., 2016; Sánchez-Bandera et al., 2020). The dating of the sites was originally achieved thanks to a combination of magnetostratigraphy and

FIGURE 2 | General views of the Oldowan sites of Barranco León and Fuente Nueva 3 sites: 1) View of the Barranco León site on the edge of the ravine (Photo: Chmiel F.L.); 2) View of excavations at the Barranco León site in 2020 (Photo: J. Cámara); 3) View of the Fuente Nueva 3 site (Photo D. Barsky); View of the *Mammuthus meridionalis* tusks *in situ* in level 5 of the Fuente Nueva 3 site (Photo: J. Cámara).

biochronology. Both sites show reverse polarity and are attributed to the Matuyama Chron, preceding the Jaramillo normal subchron (>1.07–0.99 Ma) (Oms et al., 2000a; Oms et al., 2000b; Oms et al., 2003; Oms et al., 2011). The micro-mammal assemblages of both sites place them in the regional *Allophaiomys* aff. *lavocati* biozone (Agustí et al., 2010a; Agustí et al., 2010b; Agustí et al., 2015b). A younger age for the FN3 site was attributed after the identification of evolutionary differences between the *M. savini* populations from BL and FN3 (Lozano-Fernández et al., 2015). Additional U-series and ESR dating has been carried out using quartz grains and dental materials (BL: levels D1 and D2 weighted average ESR age of 1.43 ± 0.38 Ma and FN3: age range from 1.67 to 1.34 Ma, Toro-Moyano et al., 2013; Duval, 2008, Duval et al., 2011; Duval et al., 2012a; Duval et al., 2012b), as well as cosmogenic nuclide age evaluation (burial age 1.50 ± 0.31 Ma at FN3, Álvarez et al., 2015). The biochronology supports the numerical data and the combined methodologies constrain the magnetostratigraphic readings confirming a pre-Jaramillo age for both sites and allowing to propose an age close to 1.4 Ma for BL and to 1.2 Ma for FN3.

While a water-rich environment is clearly defined for both occurrences (Anadón et al., 2003; Oms et al., 2011; García-Aguilar et al., 2014), further refinement of the climates and environments reigning during the different periods represented in each level of the BL and FN3 sites have been obtained in recent years. By combining stratigraphy, geochronology and biostratigraphy, information can be obtained about inter and intra-site variability, allowing to draw new inferences about hominin behavior and survival strategies at the sites. For example, paleoenvironmental reconstructions made by examining successive assemblages of fossil amphibians and reptiles excavated from the different levels of each sequence indicate progressive aridity through time at BL (from level D1 to level E), whereas in FN3 aridity characterizes only level 5 (Sánchez-Bandera et al., 2020). These results demonstrate flexibility on behalf of the hominins present at the sites in the face of the late Early Pleistocene climatic cyclicity (interglacial and glacial), suggesting they were able to cope with changing environmental conditions. This information has recently been buttressed by a study of amphibian body size (Martínez-Monzón

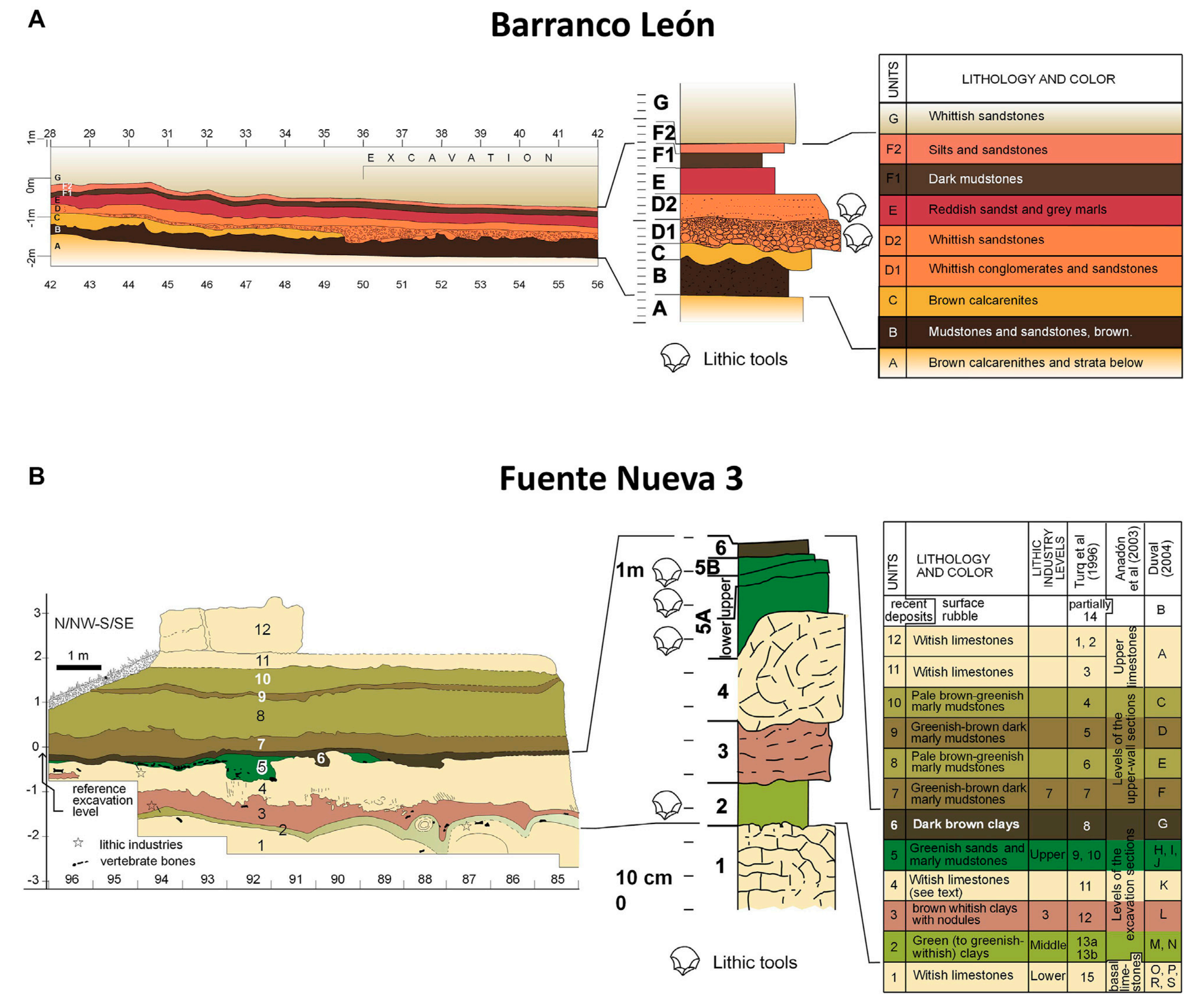

FIGURE 3 | (A) Stratigraphic section and main sedimentological features of the Barranco León site. **(B)** Stratigraphic section and main sedimentological features of the Fuente Nueva 3 site (Figures re-drawn by O. Oms after Oms et al., 2011 and Sánchez-Bandera et al., 2020).

et al., 2022), showing that female frogs became significantly smaller during the interglacial stages, when species' richness increased, while they underwent size increase during the more arid glacial periods characterized by fewer resources. Main explanations proposed to justify this pattern are the "water-availability hypothesis" and a trade-off between somatic growth and reproductive opportunities for females (Martínez-Monzón et al., 2022).

Before moving on to discuss the cultural aspects in relation to raw material procurement and use as observed from the BL and FN3 lithic assemblages, some additional observations are worthwhile noting as they allow further refinements in intra and inter-site climatic and vegetation settings that will be important when considering hominin behavior. Recently published data about the dental mesowear signals calculated from large mammals (e.g., elephant, hippo, horse) and indicative of their browsing or grazing diets (with a more abrasive grass-rich diet showing flatter wear angles), shows that browsers or mixed feeders dominated at both BL and FN3, while mainly grazers were present at VM (Saarinen et al., 2021). This evidence underlines the harsher climatic conditions dominating during the formation of the VM paleontological site, suggesting that the arrival of hominins in western Europe occurred during a more clement period of climatic conditions at the BL and FN3 sites. In this study, mean annual precipitation, temperature of coldest month and net primary productivity were estimated for the GBB sites based on dental trait distribution in the large herbivorous mammals, and compared with African Pleistocene hominin sites and values for modem biomes. Moreover, the predominance of browsing large mammals in FN3 and BL indicate an environment where grasses were scarce. This significantly changes the commonly held 'savannastan' hypothesis (*sensu* Dennell and Roebroeks 2005), whereby it was assumed that the first hominins moved into western Europe because of savannah-type conditions presumably analogous to those of their 'african homeland'. Main results show that climate and vegetation in VM were roughly similar to a Mediterranean forested steppe, while evergreen Mediterranean forests and woodlands or shrub lands dominated during the hominin occupations of BL and FN3. Similarly, carbon and oxygen stable isotopes analyses carried out using tooth enamel from large herbivore dental remains excavated from VM, BL and FN3 (Bocherens et al., 2020), suggests more significant seasonal variations in aridity and vegetation at VM, confirming a harsher climate setting there in comparison with the BL and FN3 hominin sites. All of these multidisciplinary analyses contribute to changing the picture of Oldowan hominin ecological flexibility in southwestern Europe 1.4 to 1.2 Ma, while also highlighting important differences between the Oldowan sites; with BL being globally more humid with more diverse vegetation than FN3.

2.2.1 Barranco León Stratigraphic Sequence

The BL site is situated within a 70 m thick section of alluvial and lacustrine deposits exposed after the formation of the ravine (Barranco). Divided into 10 levels (Anadón et al., 2003), the site's stratigraphic sequence (**Figure 3A**) shows a thickness of some 2 m and is composed of a series of different strata of carbonated clays and siltstones, limestone, sand and conglomerates that include some sterile levels with micro and macro paleontological remains. The D level (BL-D previously BL-5) that has yielded the bulk of the lithics and a broad spectrum of faunal remains, including a dental fragment attributed to *Homo* sp. (Toro-Moyano et al., 2013), has been divided into two different levels (levels D1 and D2, Anadón et al., 2003; Oms et al., 2011). As indicated above, an age close to 1.4 Ma has been determined for the anthropic occupation of level D1 (Toro-Moyano et al., 2013). Levels D1 (65 cm thick) and D2 (20 cm thick) correspond to two distinct phases of deposition (Oms et al., 2011; Titton et al., 2021), accounting for high taphonomic variability characterizing the lithic and paleontological finds. Level D1 (deposited on the sterile archeo-stratigraphic unit C composed of calcarenite) was formed during a phase of high energy water transport and is characterized by an accumulation of (limestone) gravels, pebbles, cobbles, as well as some large-sized slabs (Oms et al., 2011; Titton et al., 2021). Contrastingly, level D2 is a compact deposit of greyish bio-plastic sands accumulated by *in situ* sedimentation. Level D2 was subsequently overlain by the dark green-colored clastic mudstone deposits of level E, containing only sparse archeological evidence.

2.2.2 Fuente Nueva 3 Stratigraphic Sequence

The FN3 site contains a stratigraphic section some 5 m thick with a total of 12 distinct levels of sedimentation, two of which (level 2 and level 5) have yielded most of the archeological and paleontological finds (with only sparse remains reported from levels 1 and 3). The sequence (**Figure 3B**.) is mainly composed of limestones, mudstones and sandstones (Oms et al., 2011). The age of the succession has been measured using magnetostratigraphy (within the negative Matuyama chron) and radiometric dating refined by biochronology (Oms et al., 2000b; Duval et al., 2012a; Duval et al., 2012b; Álvarez et al., 2015; Lozano-Fernàndez et al., 2015) and is presently fixed at close to 1.2 Ma. Situated on the Baza lake margin, the FN3 lacustrine-palustrine sequence corresponds to gradual sedimentation within the late Early Pleistocene successive climatic events, wherein the anthropic layer 5 accumulated in a colder, glacial period, relative to the warmer and more humid conditions of level 2 (Sánchez-Bandera et al., 2020). The two anthropic layers are separated by mainly sterile sediments of level 3 (brown whitish clays with carbonated nodules) and sterile level 4 (whitish limestones). Recent excavations have allowed to divide level 5 (composed of green-colored sands and marly mudstones) into at least two sublevels (superior and inferior), based on lateral variations of facies and taphonomic alterations. Sedimentological features of level 5A present lateral variation and are studied micromorphologically, leading to its sub-division in correspondence with climato-contextual events (Jiménez-Arenas et al., 2021): level 5B (composed mainly of dark-brown clays), yields fragmented and small-sized bone fragments and sparse lithics and represents a relatively humid period of lake expansion. Meanwhile, level 5A (superior and inferior, composed respectively of cemented and loosely compacted green sands and lutite) is related to a colder and dryer climatic episode (Oms et al., 2011; Sánchez-Bandera et al., 2020). The entire sequence shows sloping towards the southwest and has been quite deeply affected by different taphonomic forces, including high salt content and water flow, as well as gravitational damages that have caused some faulting and otherwise affected the integrity of the sections. As the name of the site suggests, the landscapes of FN3 (past and present) have been affected by the presence of water that likely attracted the hominins and other animals to the area for thousands of years.

3 MATERIALS AND METHODS

3.1 Excavations

Fieldwork at both sites has continued nearly uninterrupted since their discovery in the 1990s. The excavations in extension have followed the three-dimensional Cartesian 1 m^2 grid projection method commonly used to excavate Paleolithic sites (Laplace, 1971). Each square of the grid is named following the correspondence for the X and Y axes (respectively, letters and numbers). Excavations follow the sedimentary levels, attributing the archeo-paleontological materials to the identified layers to gain global vision of each sedimentary event. Spatial relationships are recorded to discern the original paleotopography of each level. While different research teams have worked at the sites over the years, excavations since 2010 have followed uniform protocols, facilitating the exploitation of homogenized databases to exploit

TABLE 2 | Types of rocks identified macroscopically in the lithic series of Barranco León and Fuente Nueva 3 (after Grégoire, 2009; Toro-Moyano et al., 2010).

Barranco LEÓN

Code BL	Rock Type	Color	Patina	Cortex	Block Morphology
CBL 1	Siliceous limestone	Beige/green to orange			Large round cobble
CBL 2	Marly limestone	White-beige			Large round cobble
CBL 3	Oolithic limestone	White-beige		Thin, globular	Nodules
SBL 1	Flint	Green	Rare, yellow	Thin, white carbonated	Small nodules
SBL 2	Flint	Grey	Rare, white	Thin, white, porous	Large nodules
SBL 3	Flint	Beige-grey	Grey, light	?	?
SBL 4	Flint	Grey ?	Total white	?	?

FUENTE NUEVA 3

Code FN 3	Rock type	Color	Patina	Cortex	Block morphology
CFN 1	Marly limestone	Beige-grey		?	Rounded nodules
CFN 2	Siliceous limestone	Beige-orange		?	Rounded nodules
CFN 3	Siliceous limestone	Grey-beige		?	Cobble
CFN 4	Sandy limestone	White		Thin, white	Cobble
CFN 5	Fossiliferous limestone	Black		Thin with fossils	Small nodules
QZFN 1	Quartzite	Grey		?	?
SFN 1	Flint	Beige-grey ?	White to yellowish	Thin, light, siliceous	Rounded
SFN 2	Flint	Grey with white fossils	White	?	?
SFN 3	Flint	Grey	Yellowish	Carbonated or siliceous, very thin	Small rounded nodules
SFN 4	Flint	Green to orange		?	?
SFN 5	Flint	Brownish		?	?
SFN 6	Flint	Grey		?	?

different kinds of data obtained from the sites. Non-identifiable fossils >2 cm long are coordinated, as are all lithic items and identifiable faunal remains; regardless of their size. Every coordinated item is assigned to an individual record with its spatial information and, if possible, preliminary classification data. A computerized register system is used to record basic field data. Sediment collected from the excavations is washed and sieved in accordance to its provenance to recuperate smaller-sized items (i.e., micro faunal remains). All of the archeo-paleontological materials are prepared in the field laboratory (cleaning, labeling, graphic documentation and restoration tasks) and distributed for study by the specialists.

3.2 Surveying

Surveying for lithic raw materials in the vicinity of the archeological sites of BL and FN 3 sites contributes to our knowledge about hominin lithic procurement patterns and environmental contexts (availability, format and quality of raw materials accessible to hominins during the occupation of the sites). In addition, it contributes to developing a more thorough understanding about how the availability of rocks apt for knapping and pounding played a role in the occupation of these sites. Over the years, specialists have pinpointed numerous flint outcrops and their detrital areas, also defining qualitative features (Toro-Moyano et al., 2007; Toro-Moyano et al., 2010, and references). During recent surveys we verified previously documented information; geo-localized significant findings; registered changes in environmental configurations, performed photographic documentation and collected lithic samples for experimental and didactic archeology (Barsky et al., 2018; Titton et al., 2018, Titton et al., 2020; Yravedra et al., 2021). Experimental knapping/use contributes to knowledge about the mechanical qualities of the different kinds of stones found in the archeological samples. As first links in a lithic operative chain, the choices made by hominins in selecting their raw materials involved noteworthy decision-making processes (i.e. evaluation of a rock's adequacy for the task at hand: size, shape, quality, fracture mechanics). A central pillar of research on the archeological stone tools, surveying reveals important information about: 1) Raw materials (variability and availability, formal attributes, qualitative diversity); 2) Hominin behavior and selective processes (mobility and lithic transport, technological strategies applied to different rock types in accordance to: clast size, shape, quality and mechanical features and relating tool types to raw materials in accordance to these criterion) and 3) Archeological site contexts (familiarity with the geological context is essential to assess archeological situations and compare contextual features).

3.3 Petrography

Up to 2010, petrographic analysis and microscopic characterization focused on the siliceous sedimentary materials (Toro-Moyano et al., 2010) from the lithic collections (excavations up to 2004). Based on macro-characteristics, a total of 4 groups of flint and 3 groups of limestone (silicified, marly and oolithic limestone) were recognized for BL and 6 groups of flint and 5 groups of limestone for FN 3 (**Table 2**).

Thin-section petrographic research was carried out for each of the two series, allowing to group together some of these types that were found to be identical from the micro-facies point of view. In parallel, characterizing the different facies observed in the lithic assemblages, prospecting and sampling in the vicinity of the sites have made it possible to locate the main outcrops in the Jurassic formations (Baena Pérez et al., 1979) and to identify areas of secondary deposits of these same materials, while providing accurate mapping of primary outcrops and secondary deposits (Grégoire, 2009; Toro-Moyano et al., 2007, 2010). A first regional lithological repository of the Sierras of Orce and Maria has been established with the dual objective of characterizing the flints of this area and preserving reference samples for future studies (our lithic referential will be made available to researchers at the *Centro de Interpretación Primeros Pobladores de Europa 'Josep Gibert'* in Orce). Microfaciological characterization of the types of flint recognized in the lithic series and of the samples taken from the various outcrops, allow to compare between facies and thus to attribute one or more potential sources to each type of flint. Places of collection of flint blocks by hominins can thus be proposed. This study reveals that the most frequent flints in the two series come from the highly developed Jurassic Dogger formations, particularly in the Sierra de la Umbria and Cerro Gordo sectors, less than 5 Km from the sites. The SBL 2, 3 and 4 and SFN 1, 2 and 3 facies come from Bajocian limestone formations and the other types have been identified in the Barthonian and more rarely, in the Malm.

The established lithological cartography is then used as a reference to calculate the minimum and maximum supply distances for the exploitation of each flint type. A geochemical characterization was also attempted on the flints. It revealed the frequent presence of carbonate inclusions ($CaCO_3$), in particular in the flints from BL. No other element has been identified at this stage through surface analyzes using the EDX microprobe coupled with SEM observations. During this initial characterization research on the rocks from both assemblages, all the facies (flint and limestone) identified in the two lithic series were located at one or more outcrop points (except for the quartzite present in small quantities in the lithic series of FN 3). More recently, additional macroscopic observations were applied to facilitate the search for refitting or conjoining flint lithics, as well as to evaluate possible hominin selective processes concerning the limestone raw materials (Titton et al., 2018; Titton et al., 2021). Accordingly, a subdivision of the two dominant rock types (flint and limestone) was carried out, determining sub-groups *Raw Material Units* (RMUs) based on dominant macroscopic petrographic characteristics (color, texture, granulometry, cortex, presence/absence of crystallization planes, trace elements, fracture planes and inclusions; Roebroeks, 1988; Vaquero, 2008; Machado et al., 2013). Limestone cobbles with no anthropic traces from the depositional context of the BL site were included in the analysis. This method was applied to compliment previously made observations (Toro-Moyano et al., 2010) for the lithic collections up to 2018, in the framework of a PhD thesis concerning the BL assemblage (Titton, 2021). Thus, at BL, a total of 9 flint and 5 limestone RMUs were distinguished and correlated with previous determinations from Toro-Moyano et al. (2010) (Titton et al., 2018; Titton et al., 2021).

3.4 Lithic Studies

The lithic toolkits from BL and FN3 are studied using a combination of classical and innovative methodologies (Barsky et al., 2015a; Titton et al., 2020; Titton, 2021): morpho-technological analyses; description of lithic taphonomic characteristics (alteration and patina); experimental archeology; artifact's spatial distribution; investigation for refitting and conjoining lithic sets. Each lithic is examined on the basis of the criteria established by the methodology of analysis of tool categorizations (Bordes, 1961; Leakey, 1971; Clark and Kleindienst, 1974; Chavaillon and Chavaillon, 1976; Isaac, 1977; Chavaillon, 1979) and the "position" of each piece in the operational chains is determined (Carbonell et al., 1983; Carbonell et al., 1992; Geneste, 2010; Soressi and Geneste, 2011). Adhering to the concept of operative scheme (Soressi and Geneste, 2011 and references), technological features are described taking into consideration the morpho-technological identification of individual links in the different chains of action recorded in each site to examine how these might have been affected- or driven by -the circumstances in which the lithic materials were found (outcrop, detrital or *in situ* gathering; clast abundance, size, quality and shape/s). Following through on the chains of action, we examine the cause-effect relationships of these raw material's variables in terms of the gestures used by the hominins during the stone reduction processes and the technical strategies they chose. Traditionally, these observations are useful to elucidate economic considerations, as well as giving information relative to hominin cognitive capacities (generally gleaned from an evaluation of the 'complexity' of the operative schemes thus identified).

Archeometry and attribute localization are also recorded for all items (e.g., percussion marks, retouch, fractures; Laplace, 1974). In pace with deepened interests in percussive technologies during the Oldowan (for example: Assaf et al., 2020; Alperson-AfilGoren-Inbar, 2016; Arroyo et al., 2016, Arroyo and de la Torre, 2018; Barkai and Gopher, 2016; Diez-Martín et al., 2009; de la Torre et al., 2013, de la Torre and Hirata, 2015), we elaborated a special methodology to describe the specificities of the limestone macro-tools, both the non-flaked and the modified items (with or without traces of percussion; Barsky et al., 2015a). As well as being analyzed for their morpho-technological features, special attention is payed to the traces of percussion visible on the limestone macro tools (Barsky et al., 2015a; Titton et al., 2018), taking into consideration their position in relation to the volumetric features of the clasts, their dispersion and concentration and their localization in relation to the formal features of the surfaces upon which they are found (rounded surface, cutting edge, abrupt crest). This work is buttressed by experimental archeology in order to better understand the kinds of gestures and materials used by the hominins (Titton et al., 2018).

For the flint and the limestone, cores and configured tools are subject to morpho-technical analyses taking into account the features of the original clast, main percussion platform and technique (Rodríguez, 2004; Toro-Moyano et al., 2010). Exploitation strategies are determined by defining the core type (Titton et al., 2021: Supplementary Material) and supported by diacritical analysis (Baena-Preysler and Cuartero, 2006; Titton et al., 2020) to determine management phases of cores and tools (Titton et al., 2020). Extension of the removals over the core/tool surface (Rodríguez, 2004; Titton, 2021), order and type are also analyzed (Barsky et al., 2015a; Titton et al., 2020). Among the more innovative strategies, statistical analyses have been used to determine angle amplitude variability separating the facets on core tools in the identification of sub-spheroids at the BL site (Titton et al., 2020). Measurements were taken using geometric morphometric analysis of 3D models (available from Titton et al., 2020: https://sketchfab.com/TITTONETAL2019). Flakes and retouched flakes, are analyzed through mainly classical morpho-technological methodology grounded in the concept of operative schemes (Soressi and Geneste, 2011 and references therein). Core management phases are supported by flake analyses (Toth, 1985), considering residual cortex on dorsal surfaces as well as removal negative direction and number (Castañeda, 1999; Titton et al., 2021: supplementary material). Finally, fragments are analyzed in terms of their raw material, size and shape to determine production method (bipolar-on-anvil, free-hand or other).

Our holistic approach to lithic studies incorporates multidisciplinary data from studies of site formation processes and post-depositional disturbances undergone by the sequences and the artifacts they contain (Titton et al., 2021). This strategy has proven to be considerably useful to understand the life-stories of the lithics. Varying states of conservation are defined by evaluating surface alterations, as well as the presence/absence and dispersion of patina (Zaidner, 2013; Barsky et al., 2015b; Titton et al., 2018; Titton et al., 2021; Titton, 2021). Lithic taphonomy informs about the displacement of artifacts within the site, either during or after their deposition. It has also proved important for evidencing possible re-use or recycling of individual lithics, for example, through the identification of pieces with different phases of patination (Toro-Moyano et al., 2010; Titton, 2021). In addition, systematic artefact spatial distribution on horizontal and vertical projections was carried out for the BL site using data from excavations up to the year 2018 (Titton et al., 2021). The aim of this work was to better comprehend the depositional sequence and the hominin activities within the site over time. This was facilitated by the elaboration of new and updated inventory databases for the Orce Pleistocene sites hosted at the Archaeological Museum of Granada (BL, FN3 and VM, Titton, 2021; Titton et al., 2021). During this process, we gathered the spatial coordinates for a total of 11,929 pieces excavated from the BL site from 1995 to 2018 and homogenized the data available from all of the excavations. Divergent denominations of the squares were normalized using data from the field diaries and fitted within the currently used standards. In some cases, however, information was found to be lacking from excavations dating prior to 2010, thus impeding their inclusion in our spatial analysis (Titton et al., 2021). This issue was further complicated by the fact that previous excavations considered the BL level 5 to be a single level (Turq et al., 1996; Gibert et al., 1998; Martínez-Navarro et al., 2005), while later advances made in our understanding of the evolution of stratigraphic and sedimentary contexts currently allow for more precision, dividing this layer into distinct depositional events. While Anadón and colleagues (2003) distinguished two different levels (D1 and D2), this information was not effectively integrated in the excavation strategies until 2010. In spite of this, the data analyzed (Titton, 2021; Titton et al., 2021) allowed us to reconstruct a surface of 148 m^2 and to study the spatial distribution of the lithic material and faunal remains on horizontal maps and vertical projections (effectuated very 1,000 mm) over most of the excavated area (Bargalló et al., 2016; Titton, 2021; Titton et al., 2021).

Our spatial analysis further benefited from information gleaned from our investigations into identifying refitting and conjoining lithic sets at BL (Toro-Moyano et al., 2013; Titton et al., 2021). The observation of the knapping axis of each product and the directions of the negatives, are clues to linking lithic items together in their operative order. As a first step in this study, we grouped the lithics into visually identifiable RMUs to facilitate our search for connecting pieces (Cziesla, 1990). More work needs to be done to further develop this informative aspect of our research, in particular at the FN3 site where, to date, undertakings to find spatial distribution of the artifacts and the search for refitting and conjoining lithic sets have yet to be carried out on a full scale.

4 RESULTS

The Oldowan stone toolkits from BL and FN3 are characterized by a differential use of the two main available raw materials: limestone and flint. Both of these rock types were collected locally from the Jurassic age formations enclosing the sites. Over the years, different kinds of lithic studies have been undertaken on the two archeological collections, focusing at first on techno-typological and petrographic issues relating mostly to the flint items (Barsky et al., 2010; Toro-Moyano et al., 2010), while such a detailed petrographic analysis of the limestone has yet to be carried out. Early on, a dichotomous use of these two materials was made evident, with the limestone items being significantly larger-sized and the flint component marked most notably by the-typically Oldowan profile of small-sized cores and flakes ranging on average between only 2 and 3 cm in maximal length. Cut marks and traces of percussion observed on some of the large mammal remains from the two sites (Espigares et al., 2019; Yravedra et al., 2021) confirmed the use of small-sized flakes for cutting meat off of the large mammal carcasses in a presumably scavenger-type subsistence patterning and the issues of primary access to carcasses have been raised in relation to interaction among which there would also be episodes of competition with other large carnivores present coevally at the sites (Espigares et al., 2013; Yravedra et al., 2021). Compared with the relatively easy readability of the flint items, the limestone pieces present in the assemblages pose more interpretative

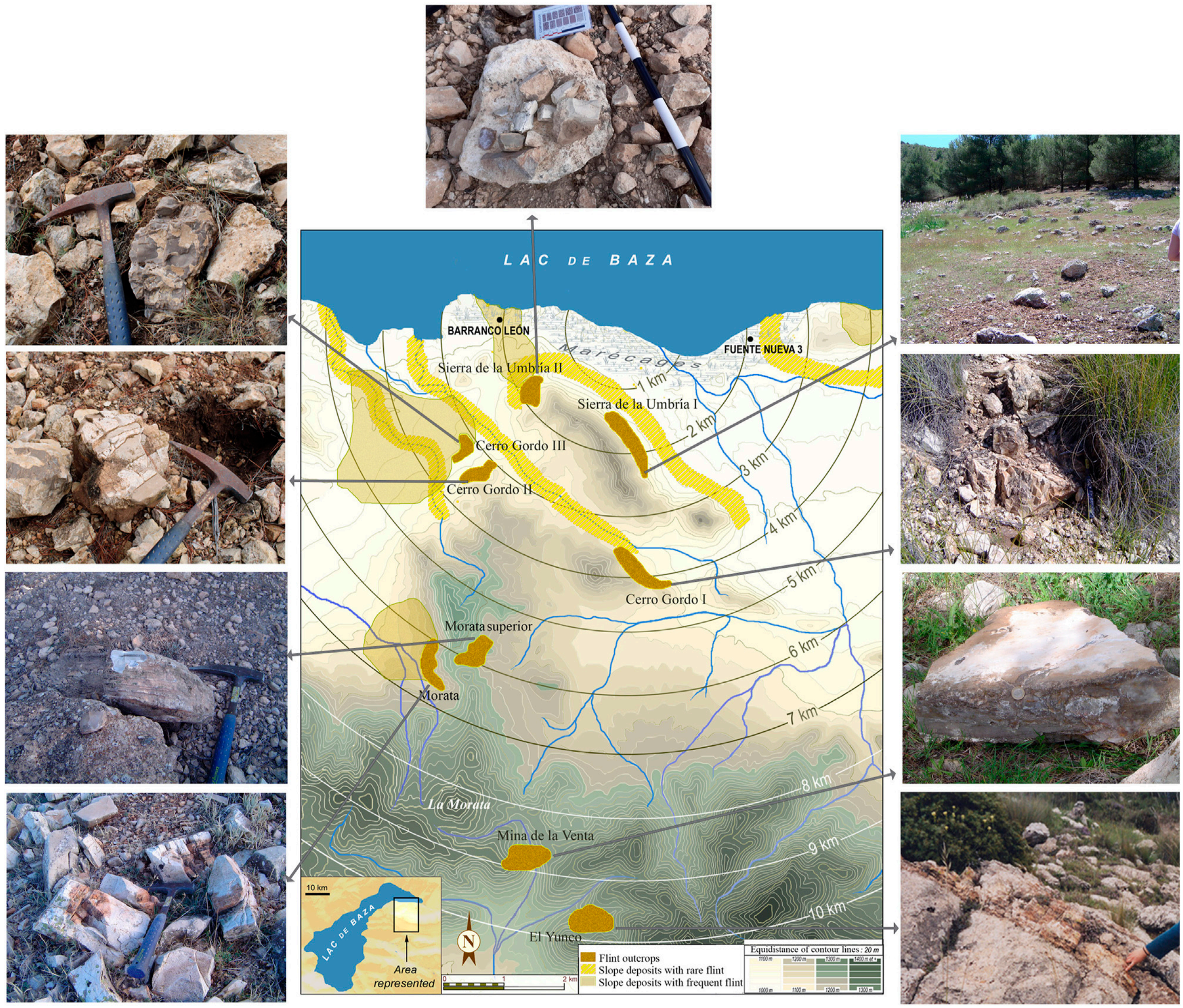

FIGURE 4 | Map showing the location of the flint outcrops and block morphology (modified after Toro-Moyano et al., 2010).

difficulties, especially due to their highly non-standardized morphologies and also to the alteration of their weathered surfaces. The natural presence of the limestone clasts within both of the sites complicates matters only further, making exact quantification of manuports or simply 'used' items virtually impossible. Finally, from 2010 onwards, a new impulse was given to the study of the limestone component of the assemblages, especially as interests in percussive activities in relation to Oldowan toolkits was increasingly growing as a pathway to better understanding the kinds of activities being performed by our hominin ancestors (Barsky et al., 2015a; Titton et al., 2018 and references). Thus, new studies have come to reveal that the Orce limestone toolkits contain not only cores and flakes, but also a relatively high diversity of tools, all relating to some form of hammering or pounding activities (active or passive). The toolkits have now become references in terms of categorizing the different types of traces of percussion thanks to an exceptionally wide array of types (defined both experimentally and archeologically) on used, knapped and configured items (Barsky et al., 2015a; Barsky et al., 2018; Titton et al., 2018; Titton et al., 2020).

Of course, the study of hominin comportments with respect to the rock types they were using goes hand in hand with other aspects of lithic analyses, in particular typological and technological considerations. In the framework of the present study, we begin with a presentation of a synthetic description of the toolkits from BL and FN3, emphasizing this special aspect of raw material's dichotomy (limestone and flint) and highlighting: 1) The availability and formal aspects of the raw materials in the landscape; 2) Tool type distribution at each site according to raw material's allocations; 3) Main morphometric features of the tool categories; 4) Reduction strategies identified for each raw material; 5) Behavioral patterning: potential uses proposed for the limestone and flint toolkits. Because numerous publications

TABLE 3 | Identified flint outcrops with their lithostratigraphic position, referential flint type denomination, block morphology and distance to the Barranco León and Fuente Nueva 3 Oldowan sites.

Outcrop Name	Lithostratigraphic Position	Flint Type Denomination	Block Morphology	Distance to BL & FN 3
Cerro Gordo I	Dogger	SFN1, SFN2, SFN3, SBL2, SBL3	Slabs, Lenticular blocks	4 Km to BL 3,5 Km to FN3
Cerro Gordo II	Dogger	SFN1, SFN3, SFN4, SBL1, SBL4	Slabs, blocks	2.8 Km to BL 5 Km to FN3
Cerro Gordo III	Dogger/Malm	SFN1, SFN2, SFN3, SFN5, SBL2, SBL3	Slabs, beds	2 Km to BL 5,2 Km to FN3
Sierra de la Umbria I	Dogger	SFN2, SFN3, SFN5, SBL2, SBL3	Slabs, beds, blocks	2.3 Km to BL 2,2 Km to FN3
Sierra de la Umbria II	Dogger	SFN2, SFN3, SFN5, SBL2, SBL3	Nodules, beds	1.2 Km to BL 3 Km to FN3
La Morata	Dogger	SFN1, SFN3, SFN4, SBL2, SBL3	Bedded blocks, nodules	6 Km to BL 6, 5 Km to FN3
La Morata superior	Dogger	All types	Slabs, beds, blocks	4.5 Km to BL 5 Km to FN3
Mina de la Venta	Dogger	SFN1, SFN2, SFN3, SBL2, SBL3	Slabs, bedded blocks	9 Km to BL 9 Km to FN3
El Yunco	Dogger	SFN1, SFN2, SFN3, SBL2, SBL3	Beds, blocks	10 Km to BL 10 Km to FN3

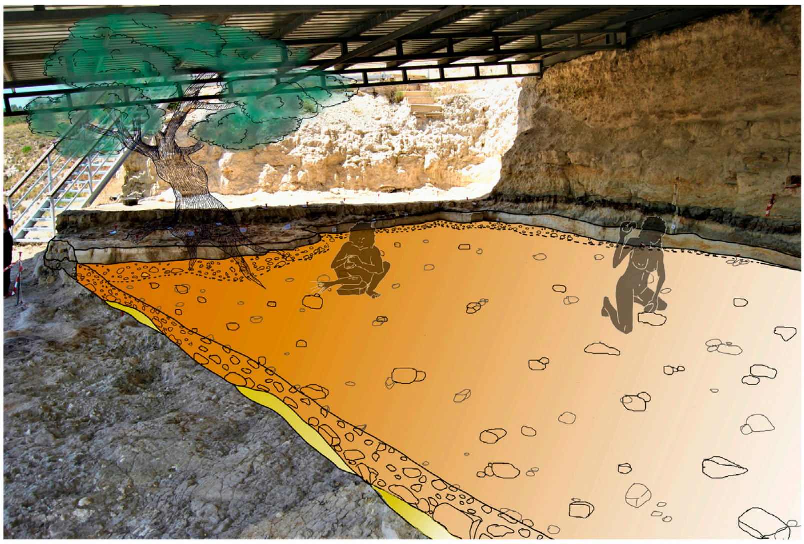

FIGURE 5 | Illustration of hominins exploiting lithic raw materials contained within layer D1 of the Barranco León site (drawn by S. Titton, Titton, 2021).

are available explaining the different tool categories and their typo-technological features (above-referenced), our focus here is on aspects relating hominin behavior to lithic raw materials and how this data has underpinned some significant differences between the BL and FN3 sites. Finally, the behavioral patterns identified are compared and contrasted with those known from other Eurasian Oldowan occurrences, in order to expand our discussion towards a wider picture of the European Oldowan and the adaptive and social practices of its little-known hominin artisans.

4.1 The Availability and Formal Aspects of the Raw Materials in the Landscape

The lithological surveys carried out between 2004 and 2006 (Toro-Moyano et al., 2010) and completed more recently (2022) have allowed to precisely assess the flint and limestone resources available in the immediate environment of the sites to within a radius of approximately 10 Km. Lithics were gathered mainly from detrital sources situated to the south of the sites in the Sierras of Orce and Maria, between the depression of the Baza paleolake to the north, and the formations of the Passillo de Chirivel to the south. In this context, 9 outcrops in primary position in Jurassic formations, mainly located in the Dogger, were geo-located, described and sampled and each of them was related to secondary deposits containing the same type of material in detrital position in the Quaternary slope deposits of the post-orogenic Chirivel basin. In total, nearly 20 localities were recognized and sampled within a radius of 10 Km (**Figure 4**). Each of these outcrops offers different types of flint in variable quantity, quality and morphology. Most of these types correspond to those identified in the lithic series of the two nearby Oldowan sites (**Table 3**).

The most abundant facies, recognized in most of the outcrops, is gray oolithic flint. However, it is not the one most selected for knapping at BL and FN 3. In terms of morphology, the Dogger flints outcrop mainly in the form of relatively thick plates (between 10 and 20 cm thick) in beds (between 30 and 40 cm), very frequently in the form of fractured tabular blocks depending on the layering of the rock, and more rarely in the form of a lenticular block. These siliceous accidents result from a diagenetic evolution of micritic carbonate deposits rich in bioclasts and appear in various forms of more or less oolithic marine flint and sometimes jasperoid of green, orange-yellow, or even red color (Baena Pérez et al., 1979). The main facies used by the hominins are accessible within a radius of 4 Km in primary and secondary position. Some secondary deposits are very close to the sites or even on the site in the case of BL, located at the mouth of a ravine rich in blocks of flint transported naturally in the slope deposits from the primary outcrops of the Sierra de la Umbria, towards the depression of the Llano de Almaida (**Figure 4**).

Even though the raw materials used at BL and FN3 were immediately available in or around the sites, we can still identify very significant differences in the contexts in relation to how these rocks were collected and used, as well as interesting economic and behavioral aspects. As we have recently shown, the Barranco León site constitutes a unique Oldowan context underlining, for the first time, the important role played by rock availability for hominins choosing their place of occupation. A combined approach of lithic analyses, taphonomy and refitting, combined with artifact spatial distribution and geology, has provided an explanation for the existence within this site of very fresh and very weathered/rolled bones and artifacts (Titton et al., 2021). According to this interpretation, the erosive surface of archeologically sterile level C was buried during a high energy flash flood depositional event (level D1) that brought a dense layer of limestone gravels, pebbles and cobbles, as well as flint nodules, into the site from a previous depositional situation located nearby to the south (see **Figure 2** in Titton et al., 2021). This event also forcibly brought in fossil bones and even knapped lithics, whose transport during this intense episode rendered them even more fragmentary, even as they endured taphonomic damages. Subsequently, a second episode occurred, characterized by the arrival of hominins to the site-perhaps attracted to this natural accumulation of limestone cobbles and flint nodules -upon which surface they performed a range of pounding, knapping and butchery activities (**Figure 5**), leaving behind a well-preserved lithic record with complete operative chains (and some refitted lithic items). This anthropic surface was subsequently covered by the *in situ* gradual sedimentary event corresponding to level D2 (which also contains archeological materials).

Given this, very unique, situation at BL, we have proposed (Titton et al., 2021) that the raw materials used in the toolkits were mostly collected from directly within the deposits themselves (level D1). Thus, the limestone component of the BL assemblage is entirely composed of slabs and cobbles. The flint, outcropping only some 1.000 m away to the south and gathered from its detrital position in the BL deposit (weathered nodules) and in the form of previously knapped items, was knapped or re-knapped (present of double patina) into the desired small-sized flakes. That knapping took place *in situ* is attested by complete operative chains and the presence at this site of very abundant tiny flakes and fragments (62.5% % of the BL assemblage, Titton et al., 2021) that we have found experimentally to be produced during knapping operations with the Orce flint (Toro-Moyano et al., 2010) that tends to be brittle and accidented.

The gathering of raw materials and economic comportments at the nearby FN 3 site were clearly somewhat different. There, hominins chose predominantly to exploit the limestone outcropping abundantly and even encasing the site; mainly in the form of blocks. Our surveys to study these outcrops revealed generally silicified limestone, presenting good mechanical quality for knapping. Limestone blocks were thus selected by the FN 3 hominins, who may even occasionally have mined-out choice materials from the outcrops (although this has not been clearly demonstrated so far). In addition, hominins exploited limestone cobbles from an unknown (but probably nearby) source. So far, agricultural activity in the vicinity of the FN 3 site has made the exact localization of this potential cobble source difficult to identify. However, given the actual situation of the Baza sector of the GBB and what is known about the paleo lake and its fresh water (thermal) sources (García-Aguilar et al., 2014), we may safely assume that (as today) the existence of a fresh water-hole scenario at FN 3 provides strong reasoning for understanding why this area attracted such a large array of fauna (including mega herbivores) and of course, hominins. In contrast to level D1 at the BL site, at FN 3 the depositional sequence is in primary context. In anthropic level 5, where conditions were considerably colder and dryer than at BL (level D1), we can envisage the hominins moving synchronically through the landscape alongside the other animals; each species taking advantage of the same, favorable conditions for life: namely, the presence of fresh water on the shores of the saline lake Baza.

In spite of the changing climatic contexts affecting the site and the shifting lacustrine and palustrine environments recorded there, this *in-situ* accumulation was affected by post-depositional alterations caused mainly by the nature of the sediments themselves (i.e., hydro plastic deformations of the clays, loss of integrity and erosion of the sands), as well as such gravitational alterations (i.e., sloping) and faulting. In spite of this, most of the herbivore and carnivore fossils are found with at least some anatomical connection still in place. In fact, an incomplete *Mammuthus meridionalis* carcass exhumed during excavations in 2001 and 2003 is described (Espigares et al., 2013). Currently, the most outstanding expression of level 5A is a thin carbonated crust containing a high concentration of firmly compacted mega to large mammals and some carnivores, as well as some sparse lithics. This unique Oldowan floor certainly represents a very long period of time when animals and hominins were gathering around this watering hole to drink and to consume plant and meat resources. Comparatively, the sedimentary package of the (older) anthropic level 2 (greenish clays), corresponds with milder, and more humid climatic conditions (Oms et al., 2010; Oms et al., 2011; Sánchez-Bandera et al., 2020). While its contents appear analogous to those of level 5 (it remains to be archeologically explored over a larger surface area), the anthropic signal appears somewhat stronger in level 2 because of an apparently denser lithic accumulation that we hope to explore further in the upcoming years. Flint resources, while available nearby in detrital position (the flint outcrop is situated ~2.000 m to the south of FN 3), were doubtless somewhat harder to come by

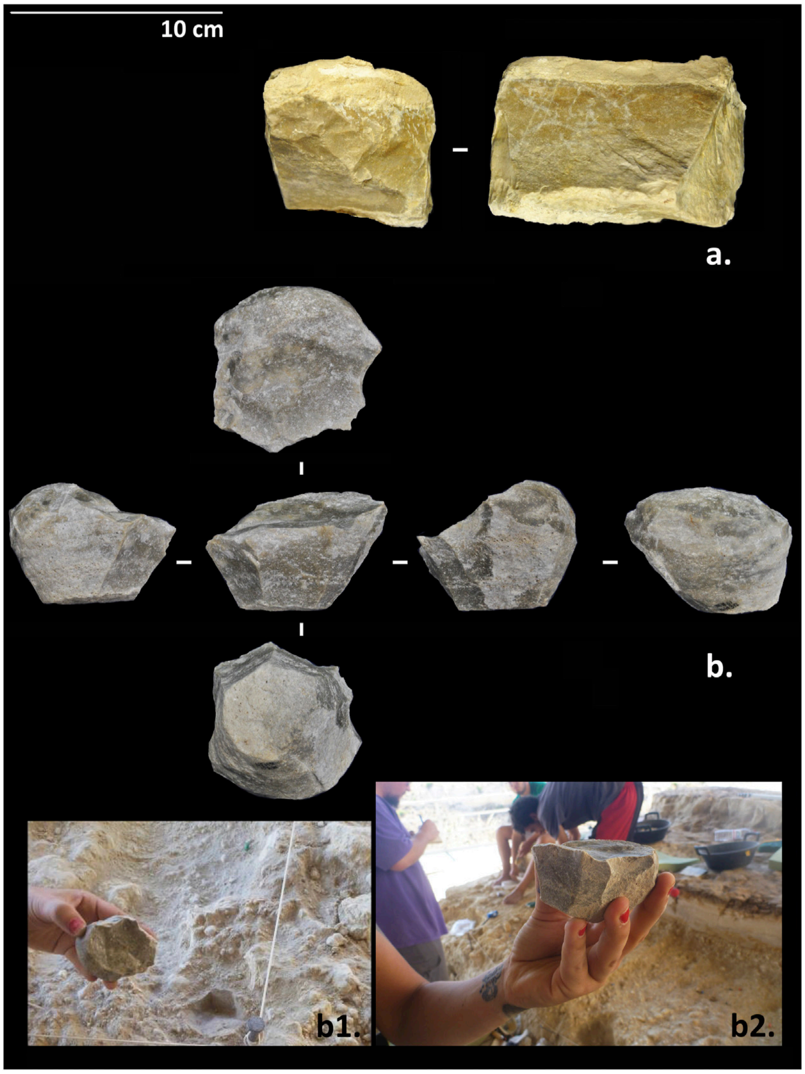

FIGURE 6 | (A) Large-sized flint clast from Barranco León (120 × 90 × 75 mm) (after Titton et al., 2021). The presence of this item in the depositional sequence flash flood event of level D1 demonstrates that at least some large-sized flint clasts were available to the hominins occupying the site. In spite of this, they continued to prefer limestone for their heavy-duty, percussive activities and systematically reserved flint for knapping small flakes; **(B)** Exceptionally large recurrent unidirectional knapped core with a perpendicular invasive surface removal (74 × 68 × 52 mm) **(B1)** Large flint core and its *in situ* imprint in level D1 and **(B2)** General view of the large flint core discovered in level D1 in 2018 (Photos **(B1,B2)**: C. Sánchez-Bandera).

then at BL (see **Section 4.4** for discussion on how this affected the flint operative schemes).

4.2 Tool Type Distribution at Each Site According to Raw Materials' Allocations

Like the majority of Oldowan toolkits, both Orce assemblages are characterized by their non-standardized character; concerning both the macro (limestone) and the smaller-sized components (flint cores and flakes). Both toolkits contain very numerous limestone implements, identified as anthropically used or modified thanks to the presence of traces of percussion, knapping and/or (occasionally) shaping. The fact that the limestone clasts were present in the depositional sequences (a flash flood accumulated at BL and encasing limestone outcrops and blocks and cobbles at FN3) makes their exact quantification impossible (and pointless) and only the identification of systematic traces of use or modification (different from naturally induced marks) are reliable for registering the anthropic signal (Barsky et al., 2015a). In recent studies, the 'cataloguing' of repeated morphologies of traces of percussion has been successfully carried out, enabling us to identify a very wide array of percussion marks that point towards an equally wide range of pounding and hammering activities being performed *in situ* at both sites (i.e., accidental removal negatives, multi-facetted scars, crush marks, *piquettage*, cupula, Barsky et al., 2015a; Barsky

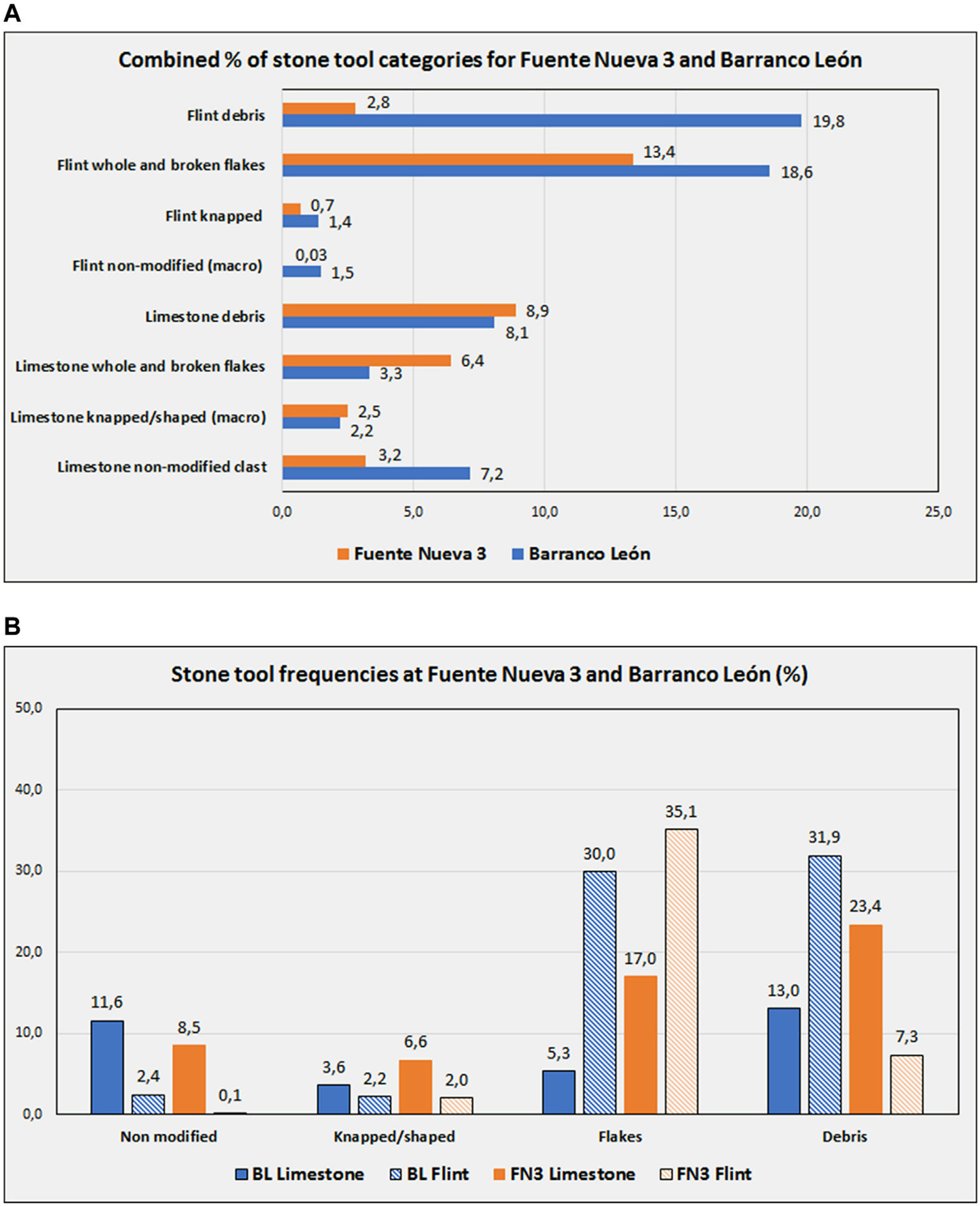

FIGURE 7 | Relative frequency of stone tool categories at Fuente Nueva 3 (FN 3) and Barranco León (BL). **(A)** The abundance of flint at BL relative to FN 3 is explained by its presence in the level D1 deposit. At both sites the limestone is well-represented in all categories, while flint shows higher frequencies among flakes and debris. The relative scarcity of flint debris at FN 3 could reflect a preference there for better quality flint. **(B)** Relative stone tool frequencies in accordance to rock types at BL and FN 3. The limestone is well-represented in all categories and dominates in the non-modified and shaped/knapped groups. Relative frequencies of flint flakes and debris illustrate the preferential use of this rock for knapping.

et al., 2018; Titton et al., 2018). In addition, the anthropic nature of the scarring observed on the limestone has been confirmed by the findings of volumetric 'regularity' in their positioning on the cobbles and blocks (in relation to their size, weight, and geometrical features). Finally, experimental research has explored the possible or probable activities (and their associated gestures) that specific sizes and shapes of percussive tools might have been used for, taking into account the kinds of materials most likely to have been available to the hominins present at the sites (i.e., wood, plant resources, tendons, bones, Barsky et al., 2018;

Titton et al., 2018). So far, our results show that at least some of these tools were effective for working soft materials (such as tendons) or for chopping wood (activities poorly identified in Oldowan sites where generally only butchery has been recognized).

There remains much to learn about the function of the limestone pounding tools and we continue to explore this theme with additional experimental work that will, in future, benefit from complementary micro-trace analyses. Optimal results and successful interpretations of tool functionality based on microscopic trace research is however, more effectively achieved from flint and, it is unlikely to obtain such high-resolution information from the altered limestone surfaces and edges. This is particularly true at BL, where limestone cobble tools often present a higher degree of alteration than at FN3, even reducing some items to no more than a powdery remnant of the original clast. Contrastingly at FN3, some of the silicified limestone tools (in particular cores and flakes) do show relatively good preservation and we hope in future to explore the possibility of performing high resolution use-wear analyses on these materials.

On the whole, clearly configured limestone tools are extremely rare. Concerning our investigative strategy however (since 2010), laying out and arranging each of the limestone collections in accordance to their main features (size, contour and section, knapping arrangement or absence thereof, etc.) was useful to recognize some repeated morphotypes. We identify pieces with strong volumetric and geometric similarities that, in some cases, even suggest a sort of 'local' standardization- or at least, some kind of mental template (Barsky et al., 2015a; Barsky et al., 2018; Titton et al., 2020). We believe that the (rare) pieces that display both morphometric and technological similarities could indicate that the hominins were using selective criterion both in their gathering of the clasts and in their technological and gestural choices. Thus, they selected the most appropriate limestone clasts (cobble or block) for making some specific items, subsequently shaping them with some intentionality in terms of their manufacture (likely in relation to a particular task). However, the specific shapes, sizes and mechanical qualities of the Orce limestone were determinant factors for the final morpho-technological outcome to such a degree that we rarely find the same items in other collections. In spite of this, a few items have been identified as fitting with the morpho-technological definitions of known Oldowan tool 'types', such as heavy-duty scrapers (present at both sites, Barsky et al., 2018) and some sub-spheroids (identified so far only at BL, Titton et al., 2020).

The lack of flint macro tools or hammerstones at both of the Orce sites (**Table 1** and **Figure 6**) *in spite of the availability of large-sized flint clasts* (either from nearby outcrops or within the depositional sequence-as at BL) demonstrates *an obvious mental link between limestone and heavy-duty percussive activities*. Conversely, such a link is equally established for the flint, which was exclusively used for the production of small flakes. It thus appears obvious that the hominins were not only capable of adapting their knapping strategies to the morphology and mechanical properties of the available raw materials, but also that they selected their raw materials in relation to the desired tools and tasks at hand. In spite of the preferential use of limestone for hammering and pounding (hammerstones, chopper-like tools and a few loosely configured items), the limestone assemblages show relative diversity, with toolkits also comprising a range of cores and flakes (described in **Section 4.4**). In fact, some tools show multiple and interchangeable phases of manufacture and use on single items (Barsky et al., 2015b; Titton et al., 2018; Titton, 2021; Titton et al., 2021). The distribution of the different elements composing the limestone assemblages at BL and FN3 indicate that these activities took place *in situ*.

The global type distribution (**Table 1**; **Figure 7**) allows to underpin subtle but significant differences between the two sites concerning flint exploitation. The clearest discrepancy between the sites concerns the relatively numerous tiny flakes and fragments at BL (many <1 cm), compared to FN3. A study carried out on these elements at BL evidenced that they display the same taphonomic duality observed on the larger lithic (and faunal) items, with some being very rolled, rounded and damaged, and others very fresh with sharp, angular edges (Cerezo-Sánchez, 2016; Titton et al., 2021). Given the interpretation of the depositional context at BL (Titton et al., 2021), we can explain this discrepancy by suggesting that the abundant tiny lithics actually form a part of the sedimentary context of level D1 while, contrastingly, the fresh items bear witness to on-site stone knapping and use on the surface of the raw material reservoir deposit (level D1). Tiny lithics present at FN 3 also attest to *in-situ* lithic manufacture and use, while their relative scarcity in level 5 could reflect a smaller number of acting individuals in relation to the very long time period likely represented by the accumulation; as supported by the micromorphological studies in progress. This relative paucity at FN3 may also reflect the findings of some of the flint-knapping activities taking place off-site and an apparent preference for better quality flint clasts.

Other behavioral aspects can be gleaned for each raw material from the relative distribution of cores and flakes at the two sites. Their proportional relationship is higher at BL, where a relative abundance of cores is noted compared with FN 3. These relationships must be considered in different ways. Looking first at the limestone, it is important to contemplate the different phases of research leading to their recognition as an integral and even dominant aspect of the assemblages. The presence of natural clasts in the deposits at both sites, as well as their varying degrees of surface alteration and a majority of only very summarily modified (or simply used) pieces, all contribute to their overall interpretative complexity. At FN 3, where some levels are characterized by whitish limestones and sedimentary contexts containing gravels and other clasts that can easily be confounded with anthropically used or modified pieces, the paucity of limestone flakes could be due (at least partially) to difficulties in on-site identification. Of course, the impetus given to the study of the limestone at both sites for over a decade now has led us to improve our strategies, guaranteeing the presence of a lithic specialist at all times during excavations, to assure recognition and proper identification based on knowledge we have gained, in particular, from our experimental research. A relative paucity of cores compared to flakes and fragments can be explained by both contextual and behavioral reasons. As we have seen, the hominins at BL were particularly interested in stone

TABLE 4 | Dimensional features of the different tool categories from Barranco León and Fuente Nueva 3 in accordance to the two main rock types. Thickness was a constant for cores on flakes in limestone from BL.

			Length		Width		Thickness	
		N	**X**	**SD**	**X**	**SD**	**X**	**SD**
BL FLINT	**FLAKES**	221	26.07	11,711	19.29	9,147	8.00	5,295
	DEBRIS < 5 mm	491	8.78	5,500	6.10	3,817	3.92	2,786
	CORES	21	46.62	27,220	34.05	21,386	25.95	19,893
	CORES ON FLAKE	3	42.33	13,013	26.00	10,392	16.00	1,000
BL limestone	**FLAKES**	17	26.82	11,897	23.59	12,390	10.12	6,421
	DEBRIS < 5 cm	106	15.01	10,044	11.60	8,126	8.04	5,941
	DEBRIS > 5 cm	131	106.61	35,412	76.00	26,462	48.16	19,473
	CORES	54	84.57	22,740	67.87	16,147	47.39	15,769
	CORES ON FLAKE	2	51.00	12,728	35.00	7,071	*	*
	HAMMERSTONES	44	109.41	49,822	84.27	36,008	58.59	22,804
	WHOLE NMC	214	93.51	34,582	71.15	26,427	46.01	19,764
FN3 FLINT	**FLAKES**	263	28.37	12,455	21.70	9,048	8.14	4,804
	DEBRIS < 5 mm	106	14.76	8,872	9.08	5,623	5.86	4,058
	CORES	9	45.22	9,189	36.00	7,937	28.00	11,136
	CORES ON FLAKE	15	41.87	16,128	29.73	14,611	14.87	5,566
FN3 limestone	**FLAKES**	105	34.32	19,880	28.27	17,224	12.32	9,293
	DEBRIS < 5 mm	294	17.15	10,269	13.04	8,596	9.04	6,163
	DEBRIS > 5 mm	60	81.43	31,335	60.88	23,476	45.58	17,553
	CORES	80	81.25	29,549	61.38	21,764	45.51	16,051
	CORES ON FLAKE	2	21.50	4,950	17.50	0.707	10.00	2,828
	HAMMERSTONES	48	91.40	36,522	69.29	27,628	53.42	19,521
	WHOLE NMC	63	58.75	38,519	46.81	27,275	33.79	21,683

**NMC, non-modified clasts. Bold letters in table indicate site names, column headings and codes.*

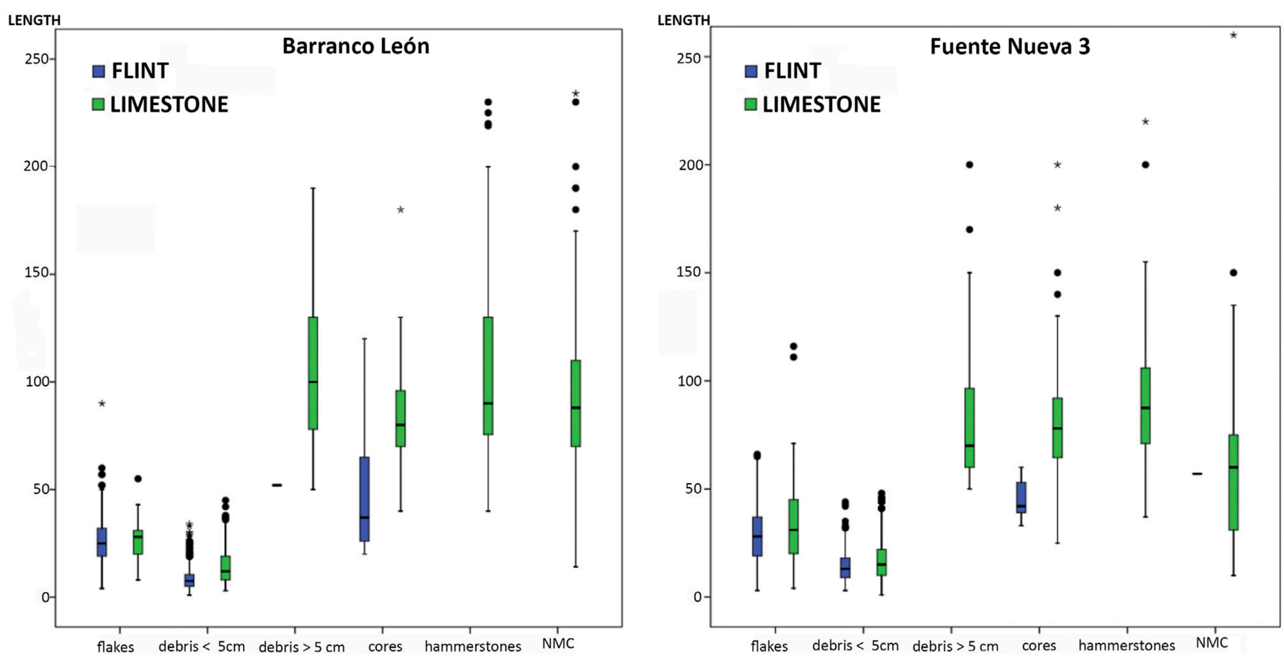

FIGURE 8 | Boxplot for the length of the main categories in BL (left) and FN3 (right): flakes (only complete), debris <50 mm, debris >50 mm, cores, hammerstones and non-modified clasts (NMC).

processing and maybe even occupied the site to take advantage of the ready availability of limestone and flint clasts in all shapes and sized (a virtual lithic supermarket!). Knapping was one of their principal activities and a number of flint cores are added to the collection as a part of the flash flood event (level D1). Some of these even display double patina, attesting that they were re-knapped during this occupational phase. Meanwhile, in the primary contexts at FN 3, hominins would have looked for detrital flint clasts in the immediate vicinity of the site. They even brought in some larger-sized flint flakes to site (Toro-Moyano et al., 2010), where they were expediently knapped to obtain the desired format of small flake (secondary knapped flakes: Zaidner, 2013; Barsky et al., 2015b). Moreover, selection has been suggested at FN3 concerning the flint, with a preference demonstrated for the finer quality with the most homogenous grain.

4.3 Main Morphometric Features of the Tool Categories

We analyzed the measurements (length, width, and thickness) of the lithic items in the assemblages of BL and FN3 (non-modified clasts, hammerstones, cores, flakes, debris <50 mm and debris >50 mm), calculating the mean and standard deviation for each group. The difference of the means was evaluated by T-Student Test, with a critical level of statistical significance of $p < 0.05$. For each site, we have explored the metric differences between tool categories and raw materials (**Table 4**; **Figure 8**).

All the non-modified clasts are only in limestone. In BL, the numerous natural cobbles have variable sizes, while at FN3 there are fewer and they are considerably smaller (BL = 93.5 × 71.1 × 46 mm and FN 3 = 58.7 × 46.8 × 33.7 mm). The difference in the means is statistically significant ($p < 0.05$). Additionally, all of the hammerstones in our samples from both sites are also only in the hammerstones from BL appear slightly larger than at FN3 limestone (BL = 109.4 × 84.2 × 58.5 mm and FN 3 = 91.4 × 69.2 × 53.4 mm), and the mean size ranges were found to be significantly different in width ($p < 0.05$) but not in length ($p = 0.053$) or in thickness ($p > 0.05$).

At BL, the average limestone core size is considerably greater than for the flint (BL: limestone cores = 84.5 × 67.8 × 47.3 mm and flint cores = 46.6 × 34 × 25.9 mm). The results for FN3 are very similar (FN 3: limestone cores = 81.2 × 61.3 × 45.5 mm and flint cores = 45.2 × 36 × 28 mm). Core size differences are statistically significant for both sites ($p < 0.05$ in all cases), perhaps due to the smaller size of flint nodules compared to the bigger limestone clasts available, or to a more intensive exploitation of the flint cores. At an inter-site level, no differences were found between flint cores from both sites ($p > 0.05$ in all cases); although they are scarcer and more homogeneous at FN3 (showing much less variance than the BL flint cores). The limestone cores do not show statistically significant size differences ($p > 0.05$ in all cases), although for FN3 the size range is greater and outlaying limestone cores can be found (both smaller and bigger).

At BL, the average size of the flint flakes is 26 × 19.2 × 8 mm and the average size of the limestone flakes is 26.8 × 23.5 × 10.1 mm, with no significant differences noted ($p > 0.05$ in all cases). At FN3, the average limestone flake size is 28.3 × 21.7 × 8.1 mm and the average limestone flake size is 34.3 × 28.2 × 12.3 mm, with the differences being statistically significant between the two raw materials for this site ($p < 0.05$ in all cases). At an inter-site level, no statistical differences were found between limestone flakes ($p > 0.05$ in all cases), but the small sample from BL could be affecting the analyses. The small difference in average for the flint flakes between sites is statistically significant for the length and width ($p < 0.05$), underpinning the small flint component of the BL assemblage. The debris <50 mm are very abundant at BL, enhanced by very small flint ones (BL flint = 8.7 × 6.1 × 3.9 mm) and statistically differentiated ($p < 0.05$ in all cases) from the bigger limestone debris (BL limestone = 15 × 11.6 × 8 mm). At FN3, the flint debris <50 mm (FN3 flint = 14.7 × 9 × 5.8 mm) are also significantly differentiated ($p < 0.05$ in all cases) from the bigger limestone debris (FN 3 limestone = 17.1 × 13 × 9 mm). Meanwhile, no differences were found for the limestone debris <50 mm between sites ($p > 0.05$ in all cases), while flint debris <50 mm from BL are significantly smaller than at FN 3. Concerning the length and width of the limestone debris >50 mm, there is a statistically significant difference between sites ($p < 0.05$) (BL = 106.6 × 76 × 48.1 mm; FN3 = 81.4 × 60.8 × 45.5) (**Figure 8** and **Table 4**).

Among the conclusions that can be drawn from these analyses, the lithic assemblage of BL is predominantly in flint and shows a clear dichotomy between raw materials: the use of flint is predominant in the small products of the assemblage, while the macro-tools are all in limestone. The importance of limestone is higher in FN 3 and, while the flint pieces are always small, the limestone items cover all size ranges, documenting not only limestone macro-tools, but also smaller items (especially limestone flakes and cores). This could be due to a choice of highly silicified limestone identified at the FN3 outcrops, which presents good mechanical quality for knapping.

4.4 Reduction Strategies Identified for Each Raw Material

A range of core reduction strategies are described in published studies for both the Barranco León and Fuente Nueva 3 sites (Toro-Moyano et al., 2010; Barsky et al., 2010). Meanwhile, our more recently published investigations have accented technological aspects of each site context (Barsky et al., 2015a; Barsky et al., 2015b; Titton et al., 2018; Titton et al., 2020; Titton et al., 2021). We summarize this information here for each site, relating it to the most outstanding feature that is: the dichotomous use of two main raw materials (limestone and flint).

Beginning with some points in common between the two sites and proceeding in the order of operative scheme outlined above, it suffices here to sum up our observations about the gathering and lithic raw material's contexts discussed in **Section 4.1**. Concerning the limestone, acquisition took place in the immediate vicinity of the sites. However, while only cobbles and slabs were used at BL, hominins at FN3 more often selected blocks than cobbles. Having not yet situated the exact

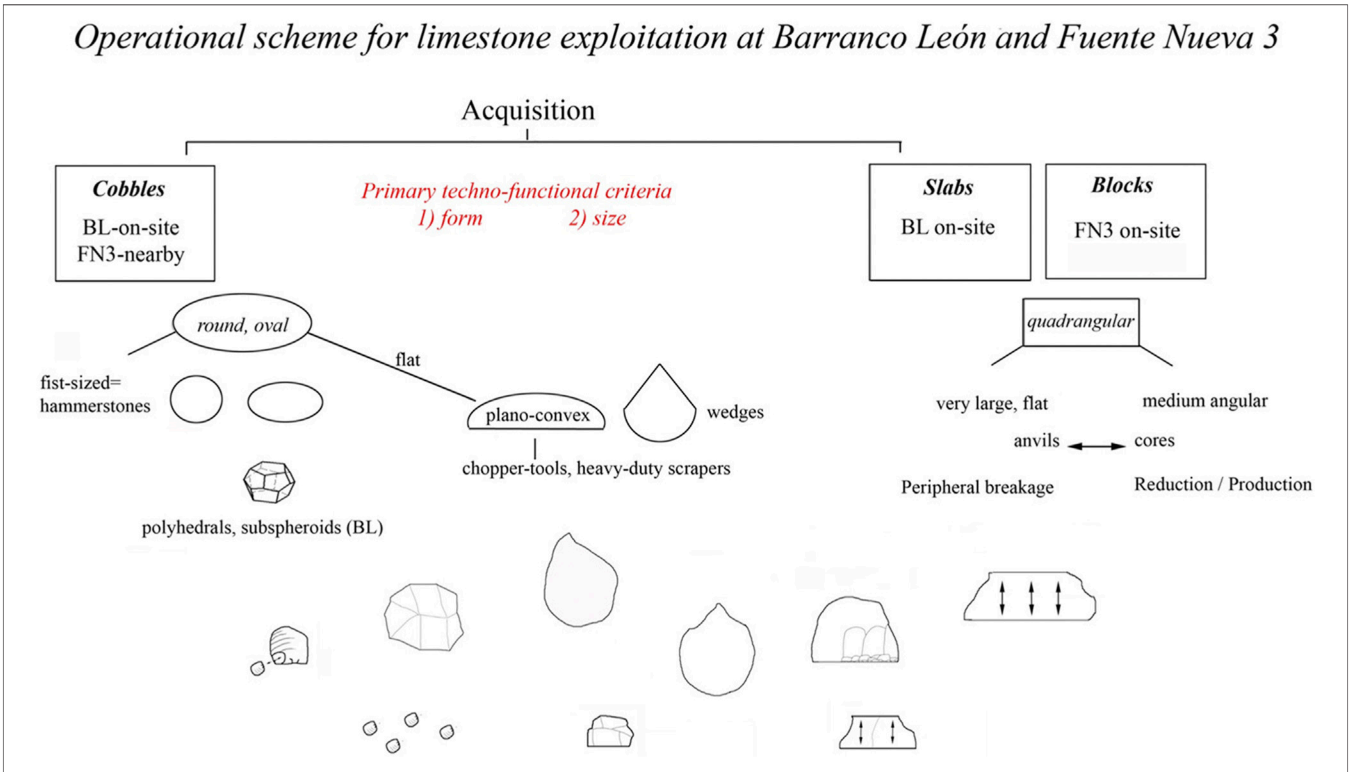

FIGURE 9 | Proposed operative schemes for the Barranco León and Fuente Nueva 3 limestone toolkits. Acquisition of clasts was in relation to primary techno-functional criteria (form and size). Typical use and/or reduction-production strategies revealing geometric morphometric choices relating to desired final product. A specific range of typical final products is identified (by D. Barsky).

provenance of these cobbles at or around the current FN3 excavation area, we might suggest that they were somewhat scarcer- or perhaps that cobbles of adequate shapes and sizes were not so readily available to the FN 3 hominins -as they were on the raw material rich pavement at BL. The FN3 hominins therefore exploited the (generally silicified and good quality) limestone blocks eroding out of the outcrops encasing the site. In both cases, limestone was available in a wide range of shapes and sizes and we have demonstrated that the choice of clasts was made in relation to the tasks at hand (Titton et al., 2018). Limestone tools used for pounding or hammering with or without modification were chosen in relation to their volumetric and morphometric features. Limestone cobbles used for flake production were more carefully selected for their quality (more silicified), as well as for the natural flaking platforms they offered (privileging parallelepiped forms). Hammerstones were (qualitatively) chosen for their compactness and present fist-size (or slightly larger) oval or rounded shapes. Slabs at BL might have served as anvils (Barsky et al., 2015a), although their highly altered surfaces impede confirmation of this hypothesis. Clearly defined anvils are conspicuously absent at both sites.

At both sites, we have identified the use of hard-hammer stone knapping using both free-hand and bipolar-on-anvil reduction methods. In some cases, we recognize the use of both methods on single items. While the bipolar-on-anvil method was more systematically used to reduce the small-sized flint nodules collected in and around the sites, it was also commonly employed to knap (and shape) the limestone clasts. Limestone clasts reduced using this method (generally of cubic shape) are occasionally recognized thanks to removal negatives with opposite impact points emanating from plane non-prepared platforms (cortex or fracture). Small-sized flint cores reduced in this way may present opposing impact traces; although our experiments have shown that this is not always the case. Flint products (flakes and fragments) produced by bipolar-on-anvil reduction also sometimes display opposite impacts, although this is hardly systematic and the method most often produces regular flakes (making quantification of bipolar-on-anvil products a meaningless exercise). Other ‘typical’ morphologies are bullet-shaped forms and/or chunk-type debris. The possibility that the so-called “pieces esquillées”, present in both assemblages (Toro-Moyano et al., 2010) could correspond to by-products of bipolar-on-anvil core reduction methods is presently being explored. Furthermore, our experiments suggest that some limestone pounding or percussion activities may have involved throwing or even block-on-block breakage (for example, for cobble opening); although these strategies need to be further supported with experimental archeology.

Limestone knapping strategies (**Figures 9**, **10**) were typically unidirectional recurrent, with the longer operative schemes

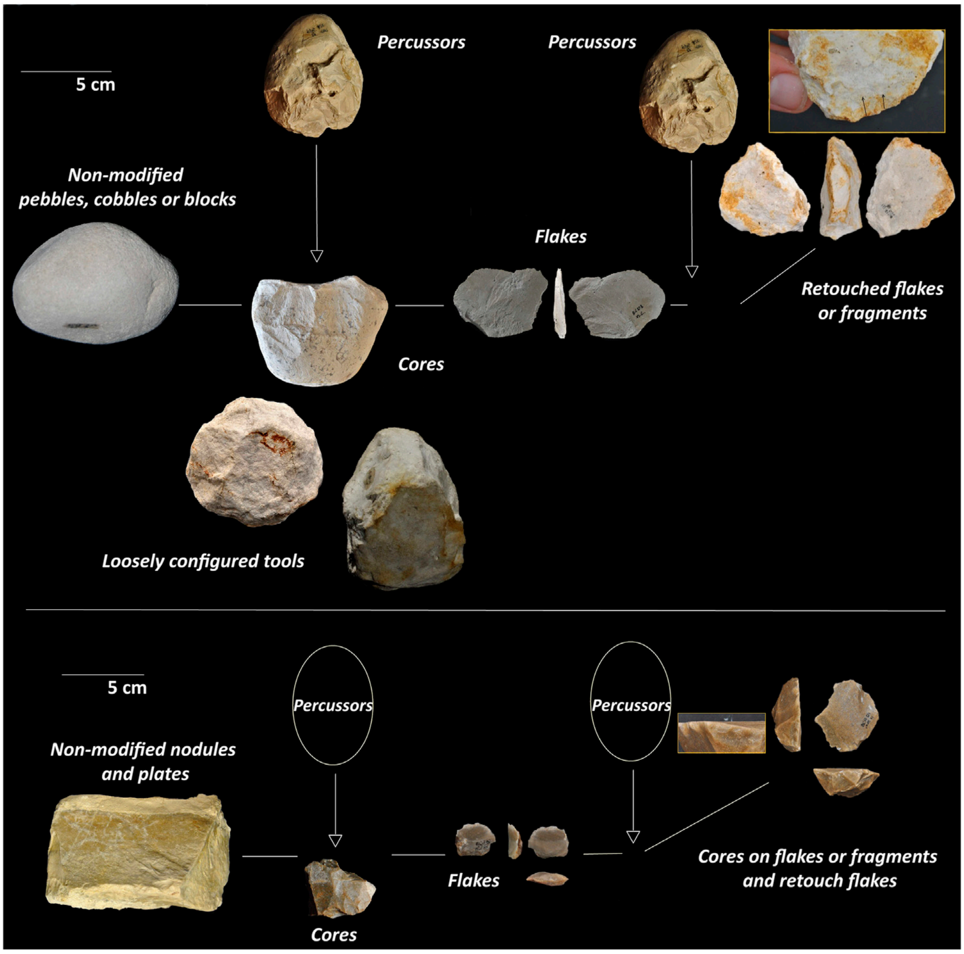

FIGURE 10 | Hypothetical limestone (upper) and flint (bottom) *chaîne opératoires* reconstructed from the Barranco León assemblage. Each category represents a distinct stage of production/use, taking into account a range of chains of action (Titton, 2021).

showing secondary phases of knapping using the platforms opened during this first phase. This was rarely, however, a multidirectional strategy (with core rotations after each removal or series of removals); but rather an orthogonal knapping tendency (the main method used at both sites to reduce limestone and flint). Multidirectional knapping has, however, been more specifically identified in the case of the sub-spheroids at BL (Titton et al., 2020). As at other Oldowan sites, centripetal strategies are incidental or absent and contingent on initial clast shape since non-prepared, generally cortical platforms were utilized with a gesture of recurrence (Barsky, 2009). Experimental flint knapping has revealed that many tiny flakes and fragments are produced from a single blow. This qualitative aspect of the Orce flint suggests that, given the overall scarcity of intentionally retouched tools and prepared platforms in the assemblages, the bulk of the tiny flakes (<2 cm) were most likely accidentally produced during knapping. Unlike for the limestone, multidirectional core forms observed among the flint at both sites result from the small size of the original nodules. There are also some cubic forms reduced using 'controlled bipolar-on-anvil' (as defined by Barsky and Lumley, 2010). While the limestone cores show shorter reduction sequences overall compared with the flint, some of the finer quality limestone (cobbles or blocks) does reflect longer knapping phases; sometimes resulting in core forms that appear more 'advanced'. Contrastingly, most of the flint cores display more exhaustive knapping series and these are present, for the most part, as small chunky fragments representative of the final phases of exploitation. This can be explained by the relative scarcity of flint compared with limestone in both site contexts.

Moving on to other observations concerning this last point that touches upon economic considerations in relation to the flint exploitation, interesting features are observed at both sites. At BL, where flint was collected directly in the pavement (level D1), one larger sized flint clast discovered in 2013 (**Figure 6A**.) does not display any signs of reduction or use: this is the only flint item discovered so far in this size range and situation. Its presence explains the existence of an exceptionally large-sized core (discovered in 2018, **Figure 6B**); the only one of its kind in the assemblage. To date, large-sized flint flakes that could correspond, for example, to this core, are not documented at BL, suggesting that some items may have been knapped and then transported off-site. So, whereas at BL even very rolled pre-knapped items were collected *in situ* and re-knapped on the surface of level D1 (Titton et al., 2021), at FN3 flint was collected a little further away and some larger-sized flakes were introduced into the site and re-knapped expediently to obtain the desired smaller flakes typical of the assemblage (Barsky et al., 2015b). All of these observations are in coherency with behaviors observed in operative schemes of the Oldowan techno-complex (**Figures 9,10**).

5 DISCUSSION AND CONCLUSION. RAW MATERIAL PROCUREMENT AND HUMAN BEHAVIOR AT BARRANCO LEON AND FUENTE NUEVA 3 IN THE CONTEXT OF THE EUROPEAN OLDOWAN

Despite the fact that our analyses of the origins of the lithic raw materials used at BL and FN 3 are revelatory of strictly local patterns of gathering associated with very little (or null) transport of the lithic clasts (Toro-Moyano et al., 2010), interesting behavioral dynamics are discerned. Meanwhile, even though different kinds of limestone and flint clasts were exploited at BL and FN3, a common denominator of stone reduction strategies is clearly identified and, we suggest, can be interpreted as truly representative of the European Oldowan with some, perhaps more advanced techno-forms (the spheroids, sparse retouched flint items and re-knapped flakes, more heavily reduced cores representative of longer operative schemes). The overall profile of the toolkits, while typically Oldowan, displays features that are specific to Orce (limestone tools with abrupt crests displaying use wear, abundance of percussive tools, alternating use of direct hammer and bipolar-on-anvil, multifunctional tools, etc.), mainly because of the particular characteristics of the raw materials that were used by the hominins occupying the area. So, while there is only very low (or null) standardization of the toolkits, these assemblages display their own characteristics in relation to other Oldowan sites, where different raw materials were used. Like other European Oldowan sites, however, the Orce hominins used a fixed set of knapping and shaping strategies that gave way to only a limited range of tool components: the small-sized flint flakes and the larger sized hammers, cores, and core-tools. The BL and FN3 archeo-paleontological occurrences are points in time and space around a saline lake in a dominantly humid but fluctuating environment, where hominins and other animals took advantage of water and rich animal and plant resources. At these sites, hominins performed not only butchery, but also a range of percussion-related activities; collecting, transporting, transforming and using local limestone and flint resources. At BL hominins obtained these materials by taking advantage of a natural lithic accumulation resulting from a flash flood event. At FN3, they exploited a natural source feeding the Orce wetlands to find limestone cobbles for hammering and pounding and also knapped silicified limestone blocks obtained from local outcrops. Flint nodules and flakes, also collected nearby, were brought to the site and expediently (re)knapped into small sharp products.

The BL and FN 3 toolkits present typically Oldowan features in line with other documented European Oldowan assemblages; with no standardized character of the artefacts dictated by opportunistic concepts (Arzarello et al., 2016). We identify: 1) tool types with recurrent morphologies (Titton et al., 2020) with evident use of their loosely configured structures (Barsky et al., 2018), in which we also recognize 2) tool multi-functionality; 3) multiple operational schemes (Titton at al., 2021, and **Figure 10**) and 3) selection of clasts in relation to primary techno-functional criteria (Barsky et al., 2015a; Titton et al., 2020). These features, along with selectivity of the raw materials, underpin that the hominins present in Europe during the late Early Pleistocene were skilled in their organization and technical management of resources. This highlights the existence of remarkable knowhow and defined mental conceptualization in the European Oldowan context (Barsky et al., 2018; Titton et al., 2020; Titton, 2021).

Comparing with data from other European Oldowan sites (age range = 1.6–0.78 Ma), (**Table 5**), we observe variability in the relative abundance of lithics composing each assemblage, relating to different factors, such as: site formation processes and excavation strategies, preservation conditions and taphonomic factors, site type and hominin *in-situ* activities. In some cases, factors relating to the collection- or not–of natural clasts that could have served non-modified for percussive activities remains problematic. The fact that most Oldowan sites are in open-air contexts and it is often impossible to determine their real extensions is also a limiting factor for determining the scope of hominin behaviors within each context. Finally, the kinds of raw materials available to hominins in and around each site also played a role in dictating the types of tools found and the technologies used to make them. Already however, hominins evidently chose knapping techniques in relation to the fracture-mechanical qualities of the materials available to them, adapting their strategies in accordance to the sizes and shapes of the clasts they used. From the settlement point of view, it is noted that, as in Africa (Howell et al., 1987; Hovers et al., 2008; Ashley et al., 2009; Hovers 2012; Stewart 2014), water-rich environmental contexts were favorable to hominin occupations in Europe (**Table 5**); assuring also a regular food supply. In spite of a dominance of open-air contexts, some variability in settlement patterns is observed, with some cave sites (Atapuerca Sima del Elefante TE9 and Gran Dolina TD6, the Vallonnet) and a basalt flowstone cavity (Bois de Riquet). In each territory, a regular water supply and food resources could indicate base camps or sheltered areas where activities always related to stone-knapping took place.

In each case, hominins adapted to the lithic resources offered by the occupied territory, recovering larger-sized clasts to use as percussion tools *in situ* (as at BL) and collecting from sources generally within a radius of 5 Km or less (**Table 5**). In most cases, flint was the preferred raw material for the smaller-sized cutting tools (flakes). The morphology of the clasts (nodules, plates, pebbles, cobbles, blocks) affected the morpho-technological features of the assemblages. The use of different materials in relation to tool manufacture is attested in various sites (e.g., BL, FN 3,

TABLE 5 | Site types and main lithic raw material's features at selected Eurasian Oldowan sites (in this table a single publication from which the information was obtained is cited for each site).

Site	Age	No of Lithics	Site Type/Setting	Lithic Raw Materials	Provenance	Selected Reference for Lithics
Barranco León	1.4 Ma	2,434	Open-air lacustrine, palustrine	Limestone slabs cobbles; flint nodules	*In situ*	Toro-Moyano et al. (2010)
Fuente Nueva 3	1.2 Ma	1,491	Lacustrine, palustrine	Limestone blocks and cobbles; flint nodules	0–5 Km	Toro-Moyano et al. (2010)
Pirro nord	1.6–1.4 Ma	340	Karst network in open environment seasonal wetland	Flint pebbles and cobbles	<5–7 Km	Berruti and Arzarello, (2020)
Atapuerca Sima del Elefante TE9	1.3 Ma	71	Cave	Chert, quartz, limestone	<2 Km	de Lombera-Hermida et al. (2015)
Atapuerca G. Dolina level TD6	0.9 Ma	999	Cave	Chert, limestone, quartzite, quartz, sandstone	<5 Km	Terradillos-Bernal and Rodríguez-Álvarez (2014)
Le Vallonnet	1.1–1.2 Ma	104	Cave	Limestone, sandstone, quartzite, flint, quartz cobbles	0–5 Km	Cauche (2021)
Pont-de-Lavaud	1.1 Ma	264 (unambiguous)	Open air, fluvial	Quartz pebbles and cobbles	*In-situ*	de Lombera-Hermida et al. (2016)
Vallparadís level 10	~1 Ma	10,613	Open-air, fluvial-marshy, alluvial/colluvial conglomerates	Quartz, flint, lyddite, quartzite, limestone, sandstone, hornfel, jasper pebbles and cobbles	0–5 Km	García et al. (2013)
Bois-de-Riquet (US2)	1–0.9 Ma	23	Basalt flowstone cavity	Basalt (encasing)	0–5 Km	Bourguignon et al. (2016)
Ca' Belvedere di Montepoggiolo	0.9 Ma	520	River delta	Flint cobbles	0–5 Km	Arzarello and Peretto (2017)
Happisburgh 3	0.99–0.78 Ma	78	Open-air: flood plain, salt marsh	Flint	-	Parfitt et al. (2010)
Bizat Ruhama	1.6–1.3 Ma	1,958	Coastal, interdune depression	Chert pebbles	<1 Km	Zaidner (2013)

Sima del Elefante TE9 and Gran Dolina TD6, le Vallonnet, Vallparadís). The flint-limestone dichotomy is a defining feature found only in the Orce sites, where these two rock types are characterized distinct operative schemes. Hominin adaptation to the materials offered by each territorial context is further highlighted by rock type variability (esp. at Vallparadís) and the use of basalt (BDR-US2) and quartz (Pont-de-Lavaud).

All of this underpins flexibility in European Oldowan hominin behaviors that shows analogous technological patterns over a period of some 1 million years: 1) selection of lithic raw material resources linked to the occupied environments (immediate vicinity: Peretto et al., 1998; Despriée et al., 2006; Barsky et al., 2010; Bourguinon et al., 2016; Titton et al., 2021; outcrops located between 1 and 7 km: Carbonell and Rodríguez, 1994; Arzarello and Peretto, 2010; García et al., 2013); 2) use of hard hammer direct percussion (Carbonell et al., 2008; Arzarello et al., 2016.) and bipolar-on-anvil methods (Peretto et al., 1998; García et al., 2013; Barsky et al., 2015a; de Lombera-Hermida et al., 2016; Mosquera et al., 2018; Titton et al., 2021); 3) stone reduction strategies dominated by unifacial techniques with unipolar, bipolar or orthogonally directed removals and, more rarely, multipolar and centripetal core forms (Desprée et al., 2006; Cauche, 2009; Arzarello and Peretto, 2010; Arzarello et al., 2012; García et al., 2013; Titton et al., 2021); 4) toolkits characterized by the abundance of small flakes; 5) ubiquitous percussive activities attested by the presence of (poorly standardized) macro-sized tools (Barsky et al., 2015b; Barsky et al., 2018; Titton et al., 2018). New, holistic approaches to lithic analysis, like the one presented here, highlight a wide range of actions and behavioral variability within these Oldowan contexts, in spite of their substantial uniformity (Titton, 2021). This new methodological approach, here focused on how raw material variability played a role in shaping hominin behaviors, provides novel interpretations to more deeply explore the multiple facets of the European Oldowan, highlighting the significance of its subtle but significant nuances.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

DB research, data collection, surveys, text and figures elaboration and Fuente Nueva 3 excavations director; ST research, data collection, surveys, excavations and text and figures elaboration; RS-R research; AB raw materials identifications for lithic refitting and surveys; SG surveying, petrography and text elaboration; TS surveying and geology; AS-R Orce site technician, database responsible, text and figures elaboration; OO Orce geologist, text and figures elaboration; J-GS Barranco León excavations director, text correction; IT-M research; JMJ-A director of the OrceProject, research, text correction.

FUNDING

This research was funded by the Junta de Andalucía, Consejeria de Cultura: Orce Research Project "Primeras ocupaciones humanas y contexto paleoecológico a partir de los depósitos pliopleistocenos de la cuenca Guadix-Baza: Zona Arqueológica de la Cuenca de Orce (Granada, España), 2017–2020" code BC.03.032/17, the Generalitat de Catalunya Research Group "Human Paleoecology of the Plio-Pleistocene" 2017SGR 859 and the Ministry of Science, Innovation and Universities (Ref: CGL2016-80975-P). The Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA) has received financial support from the Spanish Ministry of Science and Innovation through the "María de Maeztu" program for Units of Excellence (CEX 2019–000945-M). ST is beneficiary of a Margarita Salas contract (Spanish System of Science, Technology and Innovation) at Universitat Rovira i Virgili (2021URV-MS-03) funded by the European Union–NextGenerationEU, the Ministry of Universities and Recovery, Transformation and Resilience Plan. AB is supported by Juan de la Cierva-Incorporación (IJCI-2019–041546-I). JMJ-A belongs to the Excellence Unit "Archaeometrical Studies. Inside the Artefacts & Ecofacts" (University of Granada) and the Junta de Andalucía Research Group "HUM-607".

ACKNOWLEDGMENTS

The authors are grateful to C. Sánchez-Bandera for comments and corrections.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers | Frontiers in Earth Science

ORIGINAL RESEARCH
published: 26 May 2022
doi: 10.3389/feart.2022.858032

Flint Type Analysis at Late Acheulian Jaljulia (Israel), and Implications for the Origins of Prepared Core Technologies

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OPEN ACCESS

Edited by:
Marie-Hélène Moncel, Director of research CNRS-MNHN, France

Reviewed by:
Aleix Eixea, University of Valencia, Spain
Dominique Cauche, Institut de Paléontologie Humaine, France

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Specialty section:
This article was submitted to Quaternary Science, Geomorphology and Paleoenvironment, a section of the journal Frontiers in Earth Science

Received: *19 January 2022*
Accepted: *20 April 2022*
Published: *26 May 2022*

Citation:
Agam A, Rosenberg-Yefet T, Wilson L, Shemer M and Barkai R (2022) Flint Type Analysis at Late Acheulian Jaljulia (Israel), and Implications for the Origins of Prepared Core Technologies. Front. Earth Sci. 10:858032. doi: 10.3389/feart.2022.858032

Prepared Core Technologies, often considered a hallmark of the Middle Paleolithic Mousterian, have recently been observed, to some extent, in many late Lower Paleolithic Acheulian sites. This may indicate a Lower Paleolithic origin of the Levallois method, although the circumstances leading to its emergence, spread and assimilation are still debated. We aim at contributing towards this intriguing issue by studying patterns of flint procurement and exploitation at Late Acheulian Jaljulia (Israel; ~500–300 kya). We classified artifacts into flint types, using four samples: a general sample, bifaces, "regular" cores with one/two striking platforms, and prepared cores, divided into proto-Levallois, prepared (general) and discoid cores. A geologic survey located potential flint sources, and a petrographic analysis was used to assign flint types to sources. Our results show that while local Turonian flint of the Bi'na Formation dominates the general sample, selectivity in using specific flint types was observed, including among local materials. While brecciated flint types are especially common among handaxes and discoid cores, among proto-Levallois and prepared cores (general), fine-textured homogenous flint types are more common, suggesting that such flint types are better-suited when improved control over the end-product was desired. Based on our results, and following previous suggestions, we support the hypothesis that prepared core technologies in the Levant did not originate from one single technological trajectory. We support the idea that the production of predetermined blanks was based on knowledge gathered from several technological trajectories, including mainly biface shaping and the production of flakes from regular cores. This novel method was most likely transmitted time and again between individuals, gradually adjusting it to produce improved end-products. We see these conclusions as additional support for the view of prepared core technologies at the Late Acheulian as a demonstration of cumulative culture, and the existence of high-fidelity social learning mechanisms in practice already during the late Lower Paleolithic of the Levant.

Keywords: flint types, cumulative culture, Jaljulia, Late Acheulian, hadaxes, Levantine Lower Paleolithic, prepared core technologies

INTRODUCTION

The Acheulian cultural complex is the main cultural entity associated with the Lower Paleolithic of the Levant, dated to between 1.5 and 0.4 mya, and usually attributed to *Homo erectus* (sensu lato) (Bar-Yosef and Belmaker, 2011). Acheulian lithic assemblages are usually characterized by the production of flakes and flake-tools, accompanied, in variable proportions, by the manufacture of bifaces, known as handaxes, or Large Cutting Tools (e.g., Bar-Yosef et al., 1993; Lycett and Gowlett, 2008; Sharon, 2008, 2009, 2010; Barkai, 2009; Machin, 2009). These are considered the hallmark of the Acheulian cultural complex in the Levant.

The Acheulian is commonly referred to as a stagnant culture, with relatively few behavioral and technological changes in comparison to later periods (Bar-Yosef, 1994, 2006). However, while persistence of traditional ways does appear to be the rule during the Acheulian, especially concerning the production of handaxes, this may reflect the suitability of Acheulian technologies to Lower Paleolithic lifeways and adaptation (Finkel and Barkai, 2018), rather than being a limiting factor (Hopkinson et al., 2013). Moreover, significant transformations in human behaviour (such as the use of fire, the occupation of new landscapes, big-game hunting, etc.), in addition to a wide range of lithic technologies (e.g., systematic lithic recycling, the use of soft hammers), have been identified throughout the Acheulian and particularly towards the end of the Lower Paleolithic period (e.g., Nowell and White, 2010; Hopkinson et al., 2013). In recent years, the application of prepared core technologies (PCTs) aimed at the production of predetermined blanks has been demonstrated in several Acheulian contexts (e.g., Santonja and Villa, 2006; Nowell and White, 2010; Picin et al., 2013; Terradillos-Bernal, 2013; Adler et al., 2014; Garcia, 2015; Hérisson et al., 2016; Shimelmitz et al., 2016; Zaidner and Weinstein-Evron, 2016; Goren-Inbar et al., 2018; Michalec et al., 2021; Rosenberg-Yefet et al., 2021; Shipton, 2022). It is often suggested that the invention and assimilation of PCTs, seen by some as the precursors of the Levallois method, reflect a significant shift in cognitive and technological capabilities of Paleolithic populations (Ambrose, 2001; Stout, 2010; Wynn and Coolidge, 2010; Eren and Lycett, 2012; Cole, 2015; Muller et al., 2017).

In this paper, we explore patterns of flint procurement and exploitation at the Late Acheulian site of Jaljulia (Israel), with a special focus on the bifaces and PCT-related artifacts found at the site. We aim at shedding light on the considerations which influenced flint type selection in Jaljulia, and on the circumstances leading to the emergence and adoption of PCTs during the Levantine Acheulian, and their link to the concept of cumulative culture, in light of the work by Rosenberg-Yefet et al. (2021). For this purpose, we visually classified flint artifacts from Jaljulia into flint types, using four separate samples: a general sample, including artifacts from various typo-technological categories; a sample of bifaces; a sample of "regular" cores (with one or two striking platforms), and a sample of PCT-related artifacts. In addition, we performed a geologic survey, aimed at identifying potential flint sources in the vicinity of the site, and a petrographic analysis of flint thin sections, aimed at identifying the geologic origin, and the potential sources, of the flint used at the site.

THE MAIN TECHNOLOGICAL TRAJECTORIES OF THE ACHEULIAN

Generally, the Acheulian cultural complex is characterized by three major flake production technologies: the manufacture of large (over 10 cm long) flakes from giant cores for the production of bifaces; small to medium-sized flakes produced from a variety of cores; and small flakes, usually produced from "parent" flakes, often by means of lithic recycling (Lycett and Gowlett, 2008; Machin, 2009; Tryon and Potts, 2011; Agam et al., 2015; Shimelmitz, 2015; Agam and Barkai, 2018; Goren-Inbar et al., 2018; for an alternative view see; Bourguignon et al., 2004). These different core technologies demonstrate a wide variability, and often a wide range of executed activities (Rosenberg-Yefet et al., 2021, 2022). They also differ in their degree of predetermination and planning, as some demonstrate modified, prepared platforms and surfaces, while others do not. Medium-sized and small flakes are further used for the manufacture of various flake tools, used for a variety of tasks, including animal butchering, (e.g., Marinelli et al., 2021), scraping activities (e.g., Marinelli et al., 2019), and plant and tuber processing (e.g., Venditti et al., 2019b).

Handaxes, the hallmark of the Acheulian, are bifacially knapped and shaped artifacts, with a continuous cutting edge running along their contour, and a bi-convex section (Lycett, 2008; Sharon, 2009). They appear repeatedly throughout the entire Old World, starting from 1.8 mya, and until ca. 200,000 years ago in the Levant, with the emergence of the Levantine Middle Paleolithic Mousterian, and even later in Europe. Some scholars suggest that there is a trend in the size and degree of refinement of handaxes through time, with later handaxes being smaller and less refined (e.g., Jelinek, 1977; Matskevich et al., 2001; Zaidner et al., 2006). These suggestions, however, are still under debate. A recent morpho-technological study found this chrono-cultural division to be valid (Herzlinger et al., 2021a), but with Middle Acheulian bifaces to be of better craftsmanship than some of the Late Acheulian assemblages. Key (2019) has proposed, based on 2D and 3D analyses, that while the shape of Acheulian handaxes tends to be diverse and variable, their form is strongly dictated by the volume of the material used. Herzlinger et al. (2021b), however, argue, based on an analysis of Large Cutting Tools from early Acheulian 'Ubeidiya, that while the final form of thee artifacts was strongly affected by the morphological properties of the selected material, the initial choice to use this specific nodule/blank represents a purposeful selection. According to Herzlinger et al. (2021b), this reflects the advanced planning capacities of this early Acheulian population.

While the function(s) of handaxes is still under debate, Wynn and Gowlett (2018) describe the form of handaxes as being "over-determined", meaning that Acheulian knappers invested more effort in the shaping of these artifacts than was needed for their functionality. This implies that there were factors beyond functionality affecting the production of handaxes. Several studies have further stressed the possible non-utilitarian aspects of Acheulian bifaces, suggesting a more complex set of considerations in the manufacture of these artifacts (e.g., Kohn and Mithen, 1999; Carbonell and Mosquera, 2006; Shipton and White, 2020).

Another noteworthy component of Acheulian technologies is chopping tools. These artifacts are found in the archaeological record as early as 2.6 mya in Africaþ, and until 500–300 kya in Asia and the Levant (e.g., Toth, 1985; Barsky et al., 2015; Doronichev, 2016; Villa et al., 2016; Venditti et al., 2021). According to Leakey (1971), a chopper is a core-tool with an edge flaked on one or two intersected faces. While its identification as a core or a core tool is still under debate, a recent use-wear study has supported the classification of chopping tools as tools, used mainly for the chopping of hard and medium materials, most likely bones, probably oriented towards marrow extraction (Venditti et al., 2021).

Stone spheroids and polyhedrons are also well-known from Oldowan and Acheulian sites throughout the Old World (e.g., Bar-Yosef and Goren-Inbar, 1993; Mora and De la Torre, 2005; Sharon et al., 2010). Based on the finds from Olduvai Gorge, Leakey defined polyhedrons as "*. . .angular tools with three or more working edges, usually intersecting*" and spheroids as "*. . .stone balls, smoothly rounded over the whole exterior. Faceted specimens in which the projecting ridges remain or have been only partly removed are more numerous. . .*". Still, the definition of these objects remains debated, with some viewing them as hunting tools (e.g., Isaac, 1987), exhausted cores (e.g., Sahnouni et al., 1997), hammerstones (e.g., Willoughby, 1985), or battering tools (e.g., Yustos et al., 2015). Assaf et al. (2020) suggested that such stone balls from Middle Pleistocene Qesem Cave (Israel) were used for the extraction of marrow, further contributing to the interpretation of these artifacts as tools rather than cores. It was further suggested that these stone balls tend to be made of limestone, as it provided better control over the knapping process (Assaf and Preysler, 2022).

Prepared Core Technologies in the Acheulian

Prepared core technologies (PCT) of the Levantine Acheulian include proto-Levallois cores, prepared cores (general), and discoid cores (and for more details see Rosenberg-Yefet et al., 2022). PCT are unique blank production methods aimed at producing flakes or blades with a predetermined shape and size. It is said to provide greater control over the size and shape of the final item, compared to regular core technologies, through a meticulous preparation of the core in a series of removals which form the necessary core convexities and dictate the properties of the desired end products (Boëda et al., 1990; Boëda, 1995; Schlanger, 1996; Chazan, 1997; Eren and Lycett, 2012). Some suggest that it minimizes lithic waste while maximizing the end-product cutting edge (Brantingham and Khun, 2001). It has been identified in Middle Paleolithic sites in Africa, Europe and Asia, usually in contexts associated with *Homo heidelbergensis*, *Homo neanderthalensis, Denisovans* and *Homo sapiens* (e.g., Eren and Lycett, 2012; Adler et al., 2014; Hublin et al., 2017; Akhilesh et al., 2018; Hu et al., 2019; Xia et al., 2020).

Levallois cores are typically characterized by two asymmetrical platforms, separated by a plane of intersection. The lower platform is relatively thick, and serves as the striking platform. The upper platform is slightly curved and serves as the production surface. Levallois cores can produce one flake, known as linear cores/preferential cores, or a series of flakes, termed recurrent cores. These cores are divided, based on the direction of the flaking, into unidirectional, bidirectional and centripetal (Inizan et al., 1999; Shea, 2013:84–93, and for more information see; Rosenberg-Yefet et al., 2021).

While it was thought in the past that the Levallois method emerged for the first time starting with the Middle Paleolithic Mousterian, several recent studies have securely demonstrated that PCTs, some of which bear similarities with Levallois, had already appeared during the Acheulian (e.g., Chazan 2000; Tryon et al., 2005; de la Torre, 2010; Goren-Inbar, 2011; Moncel et al., 2011; Picin et al., 2013; Adler et al., 2014; Shimelmitz et al., 2016; Zaidner and Weinstein-Evron, 2016; Goren-Inbar et al., 2018; Rosenberg-Yefet et al., 2021). This suggests that the origins of the Levallois method might have been rooted in the Acheulian (Rosenberg-Yefet et al., 2021). Yet the circumstances leading to the emergence of the Levallois methods remain debated.

The recycling of handaxes as "prepared cores" for the detachment of preferential flakes (Tuffreau, 1995; DeBono and Goren-Inbar, 2001; White and Ashton, 2003; Shimelmitz, 2015), has led to proposals linking Acheulian handaxes and the emergence of PCTs, setting the stage for the more fully fledged Levallois method (Rosenberg-Yefet et al., 2021). It has therefore been suggested that Acheulian flint knappers identified the potential in the volumetric structure of handaxes and took advantage of the convexities which characterize handaxes as a "shortcut" in the reduction sequence, allowing the manufacture of predetermined blanks with only a few preparation stages (Rosenberg-Yefet et al., 2021).

In the case of Jaljulia, the term "prepared cores" was used by Rosenberg-Yefet et al. (2021) to describe three groups of cores: proto-Levallois cores, prepared cores (general), and discoid cores. The definition of proto-Levallois cores used here follows Picin (2018), who suggested that for "*hierarchized unidirectional or proto-Levallois cores . . . The core's volume is divided into two hierarchical surfaces, one a dedicated surface of striking platforms and the other a dedicated flaking surface. The striking platforms are roughly prepared and shaped by the removal of an invasive flake that creates a flat surface in five examples. However, the line of intersection of the striking platforms and the flaking surfaces is not perpendicular to the flaking axis of the predetermined blanks but instead to secant-producing flake platforms with obtuse angles. The lateral and distal convexities are roughly configured by flakes detached parallel or secant to the direction of the flaking production . . .* "

THE SITE OF JALJULIA

Jaljulia is a Late Acheulian site, located just outside the town of Jaljulia, Israel, in the southern Sharon, on the eastern margins of

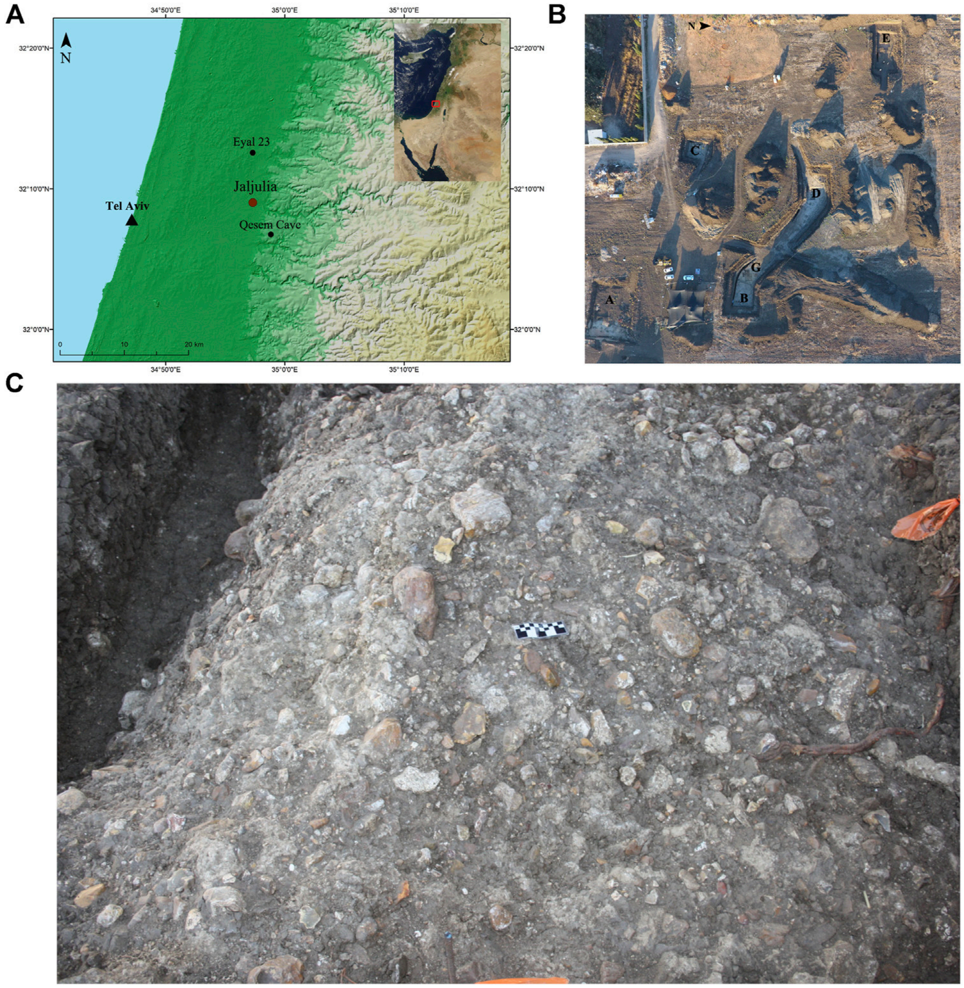

FIGURE 1 | (A) The location of Jaljulia, and major archaeological sites in its vicinity; **(B)** Aerial view of areas of excavation in Jaljulia, looking west. Note the ancient wadi in the south-eastern part of Area A (appears in light brown); **(C)** The conglomerate on top of which the site of Jaljulia was situated, as seen in Area A.

the coastal plain, about 18 km east of the present coastline (Shemer, 2019; **Figure 1A**). It is situated about 6 km south of the late Acheulian site of Eyal 23 and approximately 6 km north-west of the Acheulo-Yabrudian site of Qesem Cave (Ronen and Winter 1997; Gopher et al., 2005). Two seasons of excavation, conducted in 2017 by the Israel Antiquities Authority and in collaboration with the Department of Archaeology at Tel-Aviv University, revealed rich archaeological layers, containing abundant flint artifacts, along with a few isolated animal bones, yielded exclusively from Area D. The archaeological deposits, found at depths varying between 2 and 5 m below the modern surface, are estimated to be spread over an area of at least 1 ha, in what was a dynamic fluvial depositional environment (Shemer, 2019). Water activity was identified throughout the geological sections, implying a transition between a slowly flowing fluvial environment and a standing water body (Shemer et al., 2018).

The environment surrounding the site offered a favourable locality for the activity of early hominins, as indicated by the vast distribution of archaeological deposits, which are currently considered to be the result of several separate occupations, possibly over a long period of time (Shemer, 2019). Six areas, labelled A through G (excluding F), covering an area of approximately 80 m^2, were excavated at the site (**Figure 1B**). In Area G multiple horizons were revealed.

A typo-technological analysis of the lithic assemblages is currently underway, with preliminary results indicating that these assemblages are composed mainly of flakes and flake tools, with a notable component of handaxes, in addition to the clear presence of prepared cores. While the archaeological material presents some evidence of weathering, most of the excavated material is well-preserved (Shemer, 2019). The characteristics of the lithic assemblages have led to the preliminary assignment of Jaljulia to the Late Acheulian; chronometric dates are still pending but this indicates an expected time range between 500 and 300 kyr. (Shemer et al., Accepted). A paper providing a detailed presentation of the site's chronology and stratigraphy is soon to be published (Shemer et al., 2022).

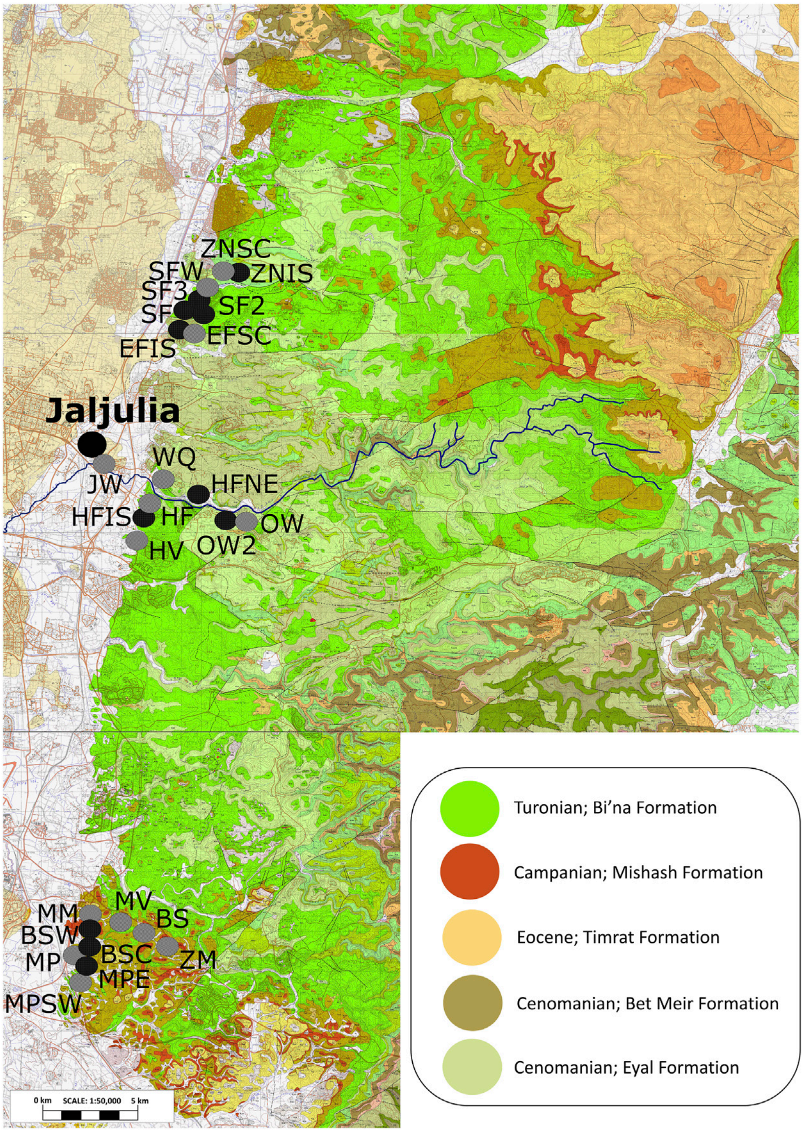

FIGURE 2 | The geologic setting of Jaljulia, and the potential geologic flint sources located (**Table 4**). Primary sources are marked by dark circles; secondary sourcesare marked by light grey circles. Note Wadi Qanah and its tributaries, marked by a dark blue line, running from east to west.

A use wear analysis of the Jaljulia bifaces has demonstrated the processing of hard materials, most likely animal remains, mainly using percussive activities (Zupancich et al., 2021). Prepared cores demonstrate the application of both proto-Levallois production and Discoid production (Rosenberg-Yefet et al., 2021, 2022). Rosenberg-Yefet et al. (2021) argue that Jaljulia PCT-related artifacts reflect an investment of effort in artifact production, pre-planning of the knapping process, and a well-established body of knowledge concerning their manufacture. Rosenberg-Yefet et al. (2022) further argue that the well-established appearance of prepared cores in Jaljulia, as well as in Late Acheulian Revadim, testifies for the emergence of concepts associated with the Levallois method.

THE GEOLOGIC SETTING

Jaljulia is located within a Turonian (Upper Cretaceous) terrain, known to contain many exposures of flint-bearing limestone of the Bi'na Formation (Hildebrand-Mittlefehldt, N. 2011; **Figure 2**). The site was deposited immediately above an ancient conglomerate (**Figure 1C**), a remnant of the floodplain of the nearby Wadi Qanah, which flowed from the east (Shemer, 2019). In Area A of the site, an ancient streambed was uncovered, representing most likely an old channel of Wadi Qanah (**Figure 1B**). Jaljulia sits 100 m north of the current channel of the wadi, which flows from south of Mount Gerizim, through the Sharon Plain, just south of Jaljulia, and westwards to the Mediterranean (**Figure 2**). Both the ancient and the current wadi channels are rich in flint nodules of various shapes and

TABLE 1 | The breakdown of the general sample used in this study.

Category	Area B	Area D	Total
Shaped Items	78	87	165
Flakes	50	32	82
Cortical Flakes	18	29	47
Cores[a]	24	31	55
Core Trimming Elements (CTEs)	10	6	16
Cores-on-Flakes and their products	13	16	29
Blades	1	—	1
Cortical Blades	2	2	4
Shaped items Spalls	8	—	8
Total Number of Artifacts	**204**	**203**	**407**

[a]*Including 1 platform, 2 platform and >2 platform cores, blade cores, core fragments, and tested cores.*

TABLE 2 | The PCTs sample from Area B.

Category	Type of Blank			
	Cores	CTE	Flakes	Total
Discoid	26	—	14	40
Proto-Levallois	37	20	5	62
Prepared cores (general)	7	39	64	110
Total Number of Artifacts	**70**	**59**	**83**	**212**

sizes, originating from various geologic sources. The flint nodules available within the site's conglomerate and in Wadi Qanah were most likely a major source of the lithic materials used by Jaljulia's inhabitants (Shemer, 2019).

The eastern section of Wadi Qanah, ~25–30 km east of Jaljulia, is located near several flint-bearing outcrops of various geologic formations, including Eocene limestone of the Timrat Formation (of the Avedat Group), and Cenomanian (Upper Cretaceous) limestone of the Beit Meir Formation (Judea Group) (Sneh and Shaliv, 2012; **Figure 2**). Additionally, outcrops of Campanian (Upper Cretaceous) flint of the Mishash Formation (Mount Scopus Group) are known to exist about 25–30 km east of Jaljulia (Sneh and Shaliv, 2012).

MATERIALS AND METHODS

Materials

Two assemblages from Jaljulia, from Areas B and D, were sampled and analyzed, based on the proportions of each typo-technological category within each assemblage, and were visually classified into flint types (n = 407; **Table 1**). These two assemblages are analyzed here both individually, as two separate assemblages, and as an integrated sample. This is aimed at evaluating spatial and possible chronological differences and similarities between the different human occupations at the site. It is also used to reflect broader phenomena of flint selection and preferences during the Late Acheulian of the Levant, as well as to establish a link between the used flint types and the possible origins of Prepared Core Technologies in the late stages of the Levantine Acheulian as a whole. A detailed typo-technological analysis of these lithic assemblages will be published separately. To randomize the selection of these samples, bags of archaeological material were organized in a row, and every third bag was picked. Each selected bag was fully analyzed, until we reached a sample size of at least 200 artifacts from each assemblage (completing the analysis of the last bag), using the same criteria used in Wilson et al. (2016) and Agam (2020), based on the parameters described in detail below. The term "the general sample" appearing throughout this paper refers to this sample. Please note that while the lithic assemblages include chips, chunks and broken flakes, our sample excluded these items as we focus here on *débitage* categories only.

Separate samples included all PCT-related artifacts found in the lithic assemblage of Area B in Jaljulia, and which were available for analysis at the time of data collection (n = 212; **Table 2**), and a sample of 60 bifaces (30 from Area B and 30 from Area D). For the biface sample, all bifaces were analyzed, with no selectivity, until we reached 30 bifaces from each assemblage. The PCT-related artifacts in Jaljulia include cores, Core Trimming Elements (CTEs) and products, and are divided into three sub-types: Proto-Levallois, prepared cores (general), and discoid cores. The artifacts analyzed here follow this division. It should be stressed that PCT-related artifacts were also found in the lithic assemblage of Area D in notable proportions. However, at the time of the analysis presented here, these artifacts were not yet available for analysis. Therefore, PCT-related artifacts from Area D are not included in this current study and will be discussed elsewhere. The PCT-related artifacts From Area B are compared to the bifaces sample, the general sample, and to "regular" cores from Areas B and D with one and two striking platforms (n = 43). The 'regular' cores sample is taken from the general sample, and forms the entire component of one and two platform cores within the general sample.

Methods

The archaeological artifacts analyzed here were classified into flint types, based on their visual traits, and weighed. The flint types were labeled alphabetically by order of identification. For each flint type, at least one specimen was selected and set aside to be used in comparing and assigning subsequent pieces to flint types. Flint types were classified based on macroscopic traits, such as colour, texture, size and shape of the original nodule (if detectable), degree of homogeneity (based on size of any disturbances, divided into homogeneous, moderately homogenous and heterogenous), degree of translucency (divided into translucent, moderately translucent and opaque), traits of cortex and any visible fossils. The different flint types were then grouped based on shared traits, such as similar texture, similar patterns (e.g., stripes, spots, etc.), the presence of breccia, and more.

Different flint types are defined here by the presence of distinctive morphological and visual features. The visible traits of flint are defined as those visible to the human eye, either with or without magnification (Luedtke, 1992: 59). The differences in colour, texture, fossil presence and other visual characteristics are in many cases the expression of different geologic origins (Malyk-Selivanova et al., 1998; Milne et al., 2009; Allan and Bolton, 2017). Furthermore, texture, shape and structure may influence the quality and degree of flakeability of a flint piece (Bustillo et al., 2009), and thus its attractiveness and the likelihood of it being chosen for knapping by prehistoric people.

Potential geologic sources were located, surveyed and sampled, following the geologic maps of the region. The survey started with the local Turonian sources, and went as far as up to a distance of ~20 km south of the site (Ilani, 1985; Yechieli, 2008; Hildebrand-Mittlefehldt, 2011). Flint samples were collected from these potential sources. Campanian flint samples of the Mishash Formation, collected from the Ben Shemen Forest, located some 21 km south of Jaljulia, were also used for comparisons.

As mentioned above, some non-Turonian potential flint sources are known to exist 25–30 km to the east of Jaljulia, along the trajectory of Wadi Qana. These sources, however, were not surveyed during this study because of modern geo-political circumstances. Therefore, we have no information about the abundance of these sources, nor their extent, nature and variety, and therefore cannot include them in this study. It is also possible that the construction of roads and buildings has removed some of the flint sources which existed in the area during prehistory. Consequently, we cannot know the exact number and extent of potential sources which were available to the Jaljulia hominins. These limitations should be kept in mind in our discussion. However, while we could not fully map all potential sources around Jaljulia, the distribution of the sources which we did locate, along with the fact that the site is located immediately next to and directly above rich flint sources, may provide useful insights concerning lithic-related human behaviours at Jaljulia.

Finally, nine standard petrographic thin sections were produced and studied to better understand the geologic origin of the brecciated flint types found at the site. These include three thin sections of samples from Turonian sources; three thin sections of samples from Campanian sources, and three thin sections of archaeological samples from Jaljulia. The thin sections were manufactured in the Thin Section Shop at the Department of Earth Sciences, University of New Brunswick, Fredericton, N.B., Canada. Each thin section was described in terms of the minerals present, the grain size, micro-fossils, degree of homogeneity, and texture. The thin sections were analyzed by optical microscopy in both plane-polarized and cross-polarized light, using a ZEISS Axio Scope.A1 Polarized Light Microscope in the Prehistory lab at Tel-Aviv University, Israel, and a Leitz Wetzlar monocular polarising petrographic microscope in the Geology lab at the Saint John campus of the University of New Brunswick, Canada.

All the data presented in this paper were tested using a Chi Square Test, to evaluate whether any of the results are statistically significant. This was performed using Excel software. Only statistically significant results ($p < 0.05$) are mentioned here.

RESULTS

Flint Types and Groups of Flint Types

In total, 35 different flint types were described within the Jaljulia sample (**Supplementary Table S1**), and clustered into 10 groups (**Figures 3**, **4**; **Table 3**). The most common is Group 3, a group of brecciated flint types, followed by Group 1, a group of fine-textured, homogenous yellowish flint types, and Group 6, brown fine-textured homogenous flint types. It should be stressed that most artifacts from Jaljulia are covered by patina, and therefore do not necessarily reflect the original colours of the flint types used.

Almost a half of the general sample is of heterogenous flint (46.7%; **Figure 5A**). Another third is homogenous. The majority of analyzed artifacts (63.4%) are fine-textured (**Figure 5B**). This pattern consistently repeats itself among the different typo-technological categories.

An interesting pattern was observed among the Cores-on-Flakes (COFs; see Agam and Barkai, 2018). While most analyzed flint pieces are fine-textured (63.4%), the proportion of fine-textured flint types among the COFs is greater still (72.2%; n = 13). This difference was found to be statistically significant ($X2 = 7.59$, df = 1, $p < 0.05$). This suggests that fine-textured flint types were preferred for the production of small flakes by means of lithic recycling, possibly because of the extremely sharp edges they tend to form (Venditti et al., 2019a). On the other hand, blanks produced from COFs present lower proportions of fine-textured flint types (54.5%; n = 6). This may suggest that the desired small flakes produced from COFs were moved to other locations, either within the site, or, alternatively, out of it, while the cores and less desired flakes remained. We hope to be able to test this hypothesis by applying use-wear analysis to these samples in the future. Previous studies have shown that the production of small flakes by means of lithic recycling was an integral trajectory of flake production during the Late Acheulian of the Levant (Agam et al., 2015; Agam and Barkai, 2018). Use-wear and residue analyses of such small flakes from the Late Acheulian site of Revadim indicated their possible role in specific butchery practices that necessitate precision and accuracy (Venditti et al., 2019b, but see; Bilbao et al., 2019). This unique pattern of flint exploitation further stresses the special place of small flakes in the lives of Levantine Acheulian groups.

When comparing Assemblages B and D, a clear consistency in patterns of exploitation can be seen. Both assemblages, for instance, are dominated by fine-textured, homogenous flint types (55.1 and 53.6%, respectively). The proportions of brecciated flint types are also similar (36.3 and 37.8%, respectively). The resemblance in the patterns observed in both assemblages implies a consistency in flint exploitation and selection throughout space, and possibly time, as implied by the chronological differences between the two areas (and for more on the chronology of Areas B and D see Shemer et al., 2022). This may testify to the existence of knowledge transmission procedures among group members concerning the availability of specific flint types in specific locations, as well as concerning the suitability of specific flint types for the production of specific blanks. Preliminary (unpublished) chronometric investigations suggest that area D was inhabited around 500 kyr while area B is much younger, most probably around 330 kyr (Shemer et al., 2022). If these dates are confirmed, this might indicate long-term use of the paleolandscape and long-lasting technological traditions practiced at the site of Jaljulia.

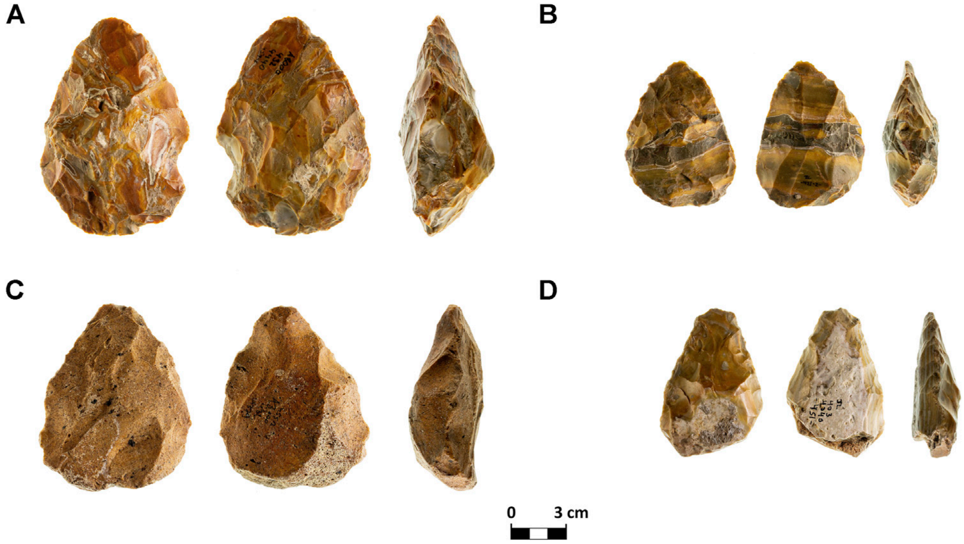

FIGURE 3 | Bifaces from Jaljulia made of flint types of interest: **(A,B)** bifaces made of brecciated, heterogenous flint types (Group 3); **(C)** a biface made of Eocene flint, with macroscopically visible nummulites; **(D)** a biface made of striped homogenous flint type (Group 8).

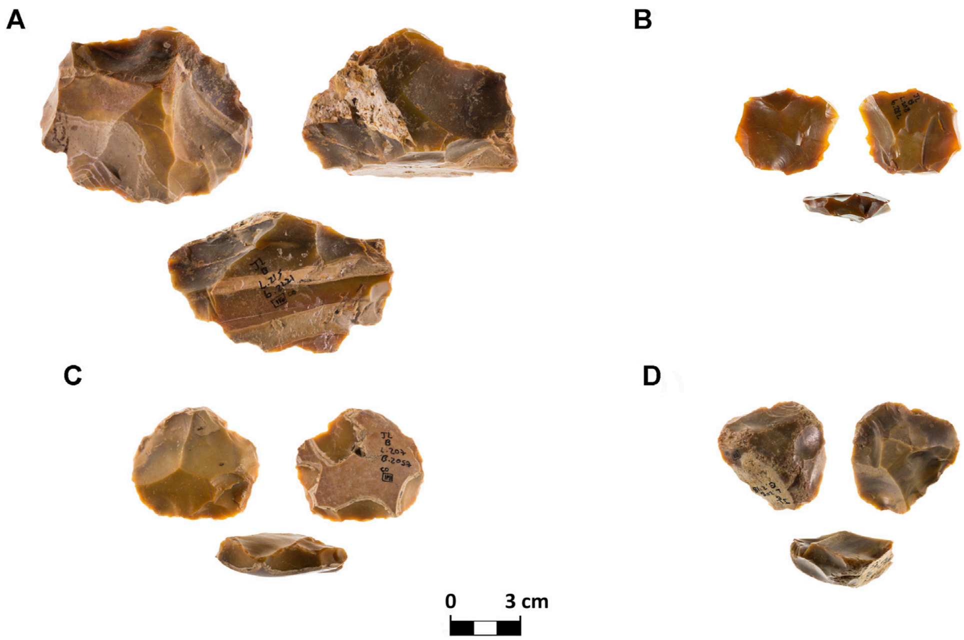

FIGURE 4 | Prepare Cores, made of flint types of interest: **(A)** a discoid core made of brecciated heterogenous flint type (Group 3); **(B)** a prepared core (general) made of brown homogenous, fine-textured flint (Group 6); **(C)** a proto-Levallois core made of fine-textured, homogenous yellowish flint (Group 1); **(D)** a proto-Levallois core made of brown, fine-textured homogenous flint type (Group 6).

PCT-Related Artifacts, Cores and Bifaces

Here we compare the results of the general sample to those of the bifaces, the PCT-related artifacts and the sample of the 'regular' cores (cores with one or two platforms). Note that the sample of prepared cores (general) includes only seven cores (**Table 2**), so these results should be treated cautiously.

"Regular" cores are the heaviest among the different core categories (with an average of 90.9 g; median: 71.0 g; n = 43), followed by discoid cores (89.8 g on average; median: 65.5 g; n = 26). Proto-Levallois cores are lighter still (74.0 g in average; median: 45.0 g; n = 37), while prepared cores (general) are significantly lighter (23.0 g on average; median: 22.0 g; n = 7).

TABLE 3 | List of the Jaljulia groups of flint types, the flint types included, their descriptions, and their frequency in the sample.

Group	Description	Flint Types Included	Qty.	%
3	Brecciated flint types	C, N, Q, R	127	31.2
1	Fine-textured, homogenous yellowish flint types	A, D, F, G, V, W, AA, AD	110	27.0
6	Brown fine-textured homogenous flint types	K, U, AB, AC	58	14.3
8	Striped fine-textured, homogenous flint types	O, S, X	27	6.6
5	Fine-textured, homogenous brown flint types with minor inclusions	H, M, Z	26	6.4
4	Fine-textured, homogenous, possibly burnt reddish flint types	E, I, J, Y	21	5.2
7	Fine-textured, homogenous spotted flint types	L, AE, AF, AJ	18	4.4
2	Coarse-textured, yellow to orange opaque homogenous flint types	B	13	3.2
9	Coarse-textured, homogenous, brown flint types, possibly with fossils	P, AG, AH, AI	3	0.7
Too weathered to be identifiable to any source	—	—	3	0.7
10	White homogenous, fine-textured, opaque flint types	T	1	0.2
Total Number of Artifacts			**407**	**100.0%**

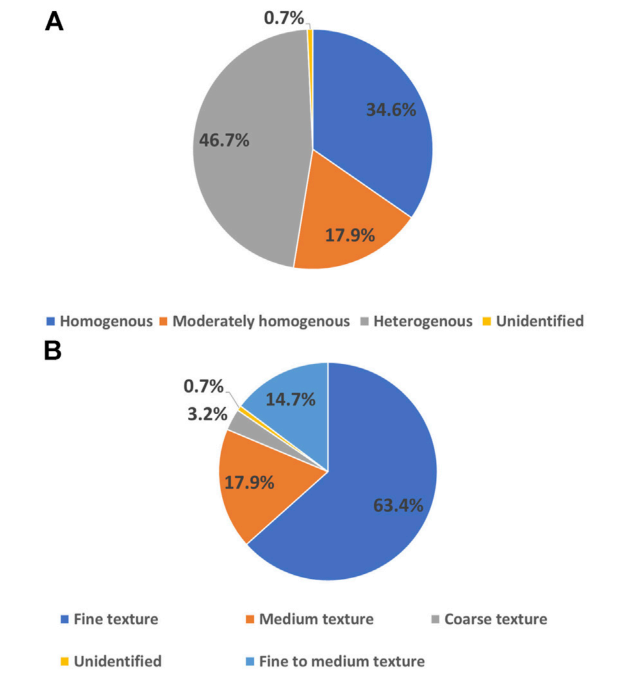

FIGURE 5 | (A) Frequency of degrees of homogeneity within the flint types of the general sample; **(B)** Frequency of flint's texture within the general sample.

Flint type C, a grey-green to orange-patinated heterogenous opaque brecciated flint type, is the most common flint type in the general sample and among the bifaces, discoid cores and proto-Levallois cores (**Figure 6A**). It is, however, significantly more common among the bifaces, while being completely absent among the prepared cores (general). The difference observed between the bifaces and the general sample was found to be statistically significant (X2 = 21.00, df = 1, $p < 0.05$).

The second most common flint type in the general sample is Type G, a light brown to orange semi-translucent fine-textured flint, with grey-yellow opaque spots (11.1%; $n = 45$). Its percentage among the "regular" cores is similar (11.6%). Its percentage among the small sample of prepared cores (general), however, is dramatically higher (4 out of 7; 57.1%; X2 = 12.99, df = 1, $p < 0.05$), while it is notably less common among the bifaces and discoid cores.

The proportions of Flint Type U, a dark brown fine-textured translucent brecciated flint type, are also of note. While it is relatively frequent in the general sample, the 'regular' cores and the discoid cores, its proportions are lower among the bifaces and the proto-Levallois cores, and it is completely absent from the prepared cores (general).

Group 3, a group of brecciated flint types, is the most common group in the general sample (31.2%; **Figure 6B**). It is, however, significantly more common among the bifaces (60.0%; $n = 36$; X2 = 19.08, df = 1, $p < 0.05$). A link between the production of bifaces and the exploitation of brecciated flint types was suggested in the past (Agam et al., 2020). This may be due to the tendency of brecciated flint types to appear in large packages, making them more suitable for biface production. Another possibility is that brecciated flint types lead to more durable tools. This suggestion, however, is yet to be demonstrated.

High proportions of Group 3 were also observed among discoid cores (69.2%; $n = 18$; X2 = 15.87, df = 1, $p < 0.05$; **Figure 6B**). The proto-Levallois cores and "regular" cores, on the other hand, present similar, lower proportions of Group 3 (**Figure 6B**). These proportions are in accordance with those in the general sample. Among the products of the discoid cores, however, the proportions of Group 3 are notably lower (28.6%; $n = 4$) than among the discoid cores, possibly suggesting that some of these are not easy to recognize, or that these products were transported elsewhere.

Group 8, a group of striped fine-textured, homogenous flint types, probably of local Turonian origin, is more frequent among the discoid, proto-Levallois and prepared cores (general) than among the "regular" cores and the general sample (**Figure 6B**). Its proportions are also somewhat higher among the bifaces, compared to the general sample and the regular cores. These proportions, however, are significantly lower than those of the brecciated flint types.

Group 1, a group of fine-textured, homogenous yellowish flint types, is also interesting. Its frequency is high in the general sample, as well as among prepared cores (general), proto-Levallois cores and "regular" cores, while being notably lower among bifaces and discoid cores.

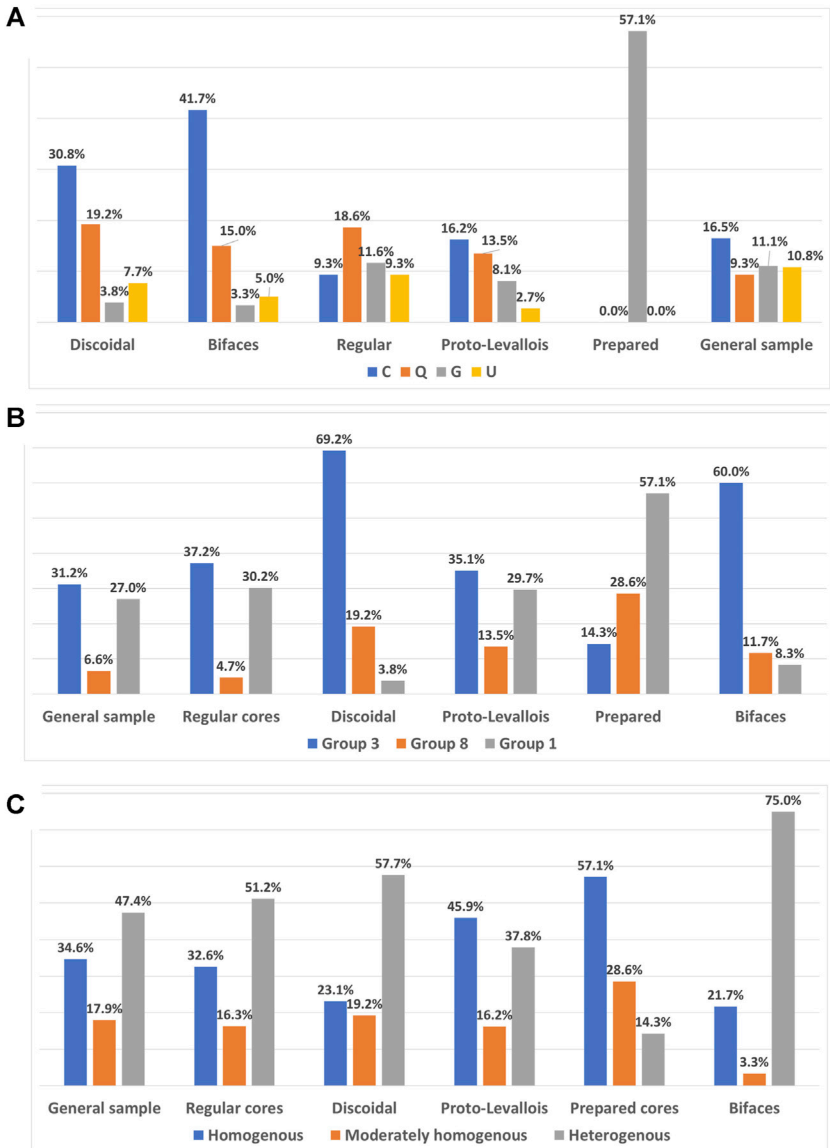

FIGURE 6 | (A) The frequency of major flint types in the general sample, the bifaces and the four core groups: discoid, Levallois, prepared (general) and "regular" cores. Note that not all flint types are included in this chart, resulting in a sum lower than 100% for each category; **(B)** The proportions of Groups 3, 8 and 1 in the different analyzed categories; **(C)** The proportions of artifacts with different degrees of homogeneity by groups.

Artifacts with patina differences (i.e., with post-patination removals) constitute 25.1% of the general sample (n = 102). Such artifacts are significantly less common among the bifaces (1.7%; n = 1; X2 = 16.65, df = 1, $p < 0.05$), discoid cores (3.8%; n = 1; X2 = 6.07, df = 1, $p < 0.05$), proto-Levallois cores (13.5%; n = 5) and prepared cores (general) (14.3%; n = 1), implying that both bifaces and PCT-related categories were more frequently manufactured from fresh blanks rather than "old" recycled blanks (but see Rosenberg-Yefet et al., 2021).

Homogenous flint types are more common among prepared cores (general) (57.1%; n = 4) and proto-Levallois cores (45.9%; n = 17) than in the other categories (**Figure 6C**). This may imply that while heterogenous flint types were often used for the manufacture of proto-Levallois cores (as implied by the notable presence of brecciated flint types), homogenous flint types were found to be better suitable for PCT production. This is further supported by the frequency of homogenous flint types among the proto-Levallois flakes (60.0%; n = 3) and the flakes produced from discoid cores (71.4%; n = 10; X2 = 7.96, df = 1, $p < 0.05$). It is possible that the success rate of flake production from such cores was higher when using homogenous flint types. Among the bifaces, on the other hand, heterogenous flint types are significantly more frequent (75.0%; n = 45; X2 = 15.92, df = 1, $p < 0.05$; see explanation above).

TABLE 4 | A full list of the identified potential flint sources.

	Name	ID	Coordinates	Age	Formation	Distance from Jaljulia (in km)	*In Situ*/ Secondary
1	Jaljulia Wadi	JW	32° 8′58.96″N, 34°57′42.79″E	Turonian? Campanian? Cenomanian?	?	—	Secondary
2	Wadi Qana	WQ	32° 8′52.49″N, 34°58′4.78″E	Turonian, Campanian?	Bi'na? Mishash? Others?	0.68	Secondary
3	Horashim Forest *In situ*	HFIS	32° 8′28.58″N, 34°58′18.38″E	Turonian	Bi'na	1.40	Primary
4	Horashim Forest	HF	32° 8′30.27″N, 34°58′23.54″E	Turonian	B'ina	1.45	Secondary
5	Horashim Village	HV	32° 8′14.56″N, 34°58′7.00″E	Turonian	B'ina	1.59	Secondary
6	Horashim Forest North-East	HFNE	32° 8′31.91″N, 34°59′9.86″E	Turonian	B'ina	2.52	Primary
7	Oranit West #2	OW2	32° 8′4.31″N, 34°59′6.64″E	Turonian	B'ina	2.86	Primary
8	Oranit West	OW	32° 7′59.81″N, 34°59′8.82″E	Turonian	B'ina	2.97	Secondary
9	Eyal Forest *In Situ*	EFIS	32°12′41.57″N, 34°59′1.80″E	Upper Cenomanian - Turonian	Eyal	7.15	Primary
10	Eyal Forest Surface Collection	EFSC	32°12′41.57″N, 34°59′1.80″E	Upper Cenomanian - Turonian	Eyal	7.23	Secondary
11	Sapir Forest	SF	32°13′12.18″N, 34°59′6.59″E	Cenomanian or Turonian	Sakhnin/Bi'na	8.15	Primary
12	Sapir Forest Wadi	SFW	32°13′13.78″N, 34°59′10.20″E	Cenomanian or Turonian	Sakhnin/Bi'na	8.18	Secondary
13	Sapir Forest 2	SF2	32°13′11.98″N, 34°59′9.19″E	Cenomanian or Turonian	Sakhnin/Bi'na	8.23	Primary
14	Sapir Forest 3	SF3	32°13′14.37″N, 34°59′9.54″E	Cenomanian or Turonian	Sakhnin/Bi'na	8.31	Primary
15	Zur Natan *In Situ*	ZNIS	32°14′24.34″N, 35° 0′42.64″E	Cenomanian	Sakhnin	11.03	Primary
16	Zur Natan Surface Collection	ZNSC	32°14′25.27″N, 35° 0′43.11″E	Cenomanian	Sakhnin	11.04	Secondary
17	Mexican Monument	MM	31°57′6.57″N, 34°56′26.50″E	Campanian	Mishash	22.08	Secondary
18	Modiin Viewpoint—Mitzpe Modiin	MV	31°56′57.52″N, 34°57′24.09″E	Campanian	Mishash	22.25	Secondary
19	Ben Shemen	BS	31°56′42.06″N, 34°58′9.07″E	Campanian (Upper Cretaceous)	Mishash	22.53	Secondary
20	Ben-Shemen West	BSW	31°56′48.19″N, 34°56′17.15″E	Campanian	Mishash	22.68	Primary
21	Ben-Shemen Center	BSC	31°56′43.39″N, 34°56′16.67″E	Campanian	Mishash	22.84	Primary + Secondary
22	The Monkeys Park	MP	31°56′38.31″N, 34°55′59.94″E	Cretaceous (Campanian?)	Mishash?	23.03	Secondary
23	Monkeys Park East	MPE	31°56′35.70″N, 34°56′8.76″E	Campanian	Mishash	23.07	Primary + Secondary
24	Monkeys Park South-West	MPSW	31°56′25.59″N, 34°55′48.15″E	Campanian	Mishash	23.47	Secondary
25	Zaglembie Martyrs (Memorial)	ZM	31°56′14.53″N, 34°59′1.06″E	Campanian (Upper Cretaceous) and/or Santonian (Upper Cretaceous)	Mishash and/or Menuha Formation	23.70	Secondary

The Potential Geologic Sources of the Jaljulia Flint Types

In total, 25 potential flint sources were found in the area surrounding Jaljulia (**Table 4**; **Figure 2**). These include Turonian sources of the Bi'na Formation, located in the immediate vicinity of the site and up to 3 km away; Cenomanian sources of the Eyal and Sakhnin Formations, located some 7–8 km north of Jaljulia; and Campanian sources of the Mishash Formation, located 22–24 km south of the site. **Supplementary Table S1** presents the association between the Jaljulia flint types and the potential flint sources, based on macroscopic and petrographic similarities, and their assignment to geologic origins; **Supplementary Table S2** presents the general sample and flint types and their assignment to geologic origins.

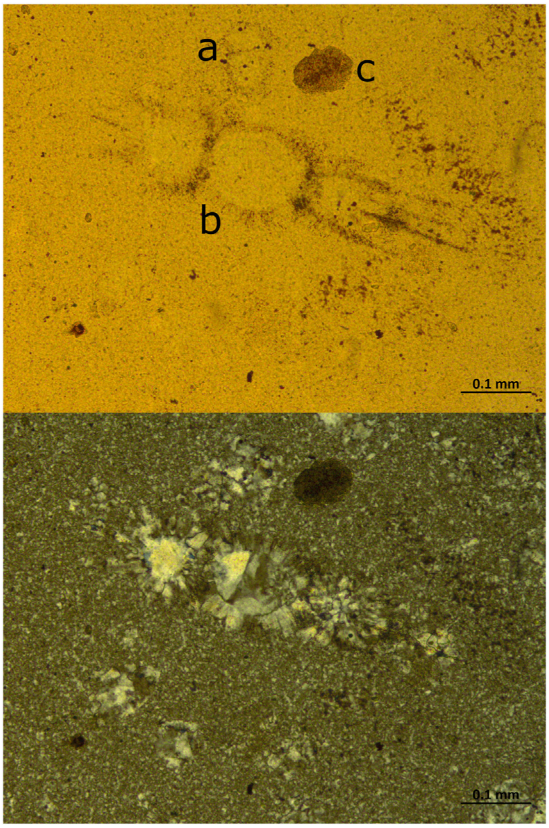

FIGURE 7 | A buliminid foraminifer (a), in plane-polarized (PP) light and in cross-polarized (XP) light, in a flint sample from Wadi Qana. Also visible in this section: a partially preserved nodosarid foraminifer (b), and a possible spore or pollen grain (c).

The site of Jaljulia is located 100 m north of the current course of Wadi Qanah, with a possible old channel of the river found in Area A at the site. Additionally, the archaeological layers of Jaljulia were deposited directly above a rich conglomerate containing plenty of flint nodules suitable for knapping (Shemer, 2019; **Figure 1C**). Therefore, it is not surprising that flint types available in the river channel were often used by the site's inhabitants. Furthermore, it is likely that these local rich secondary sources of flint deposits played a part in the decision to settle at the location in the first place and to keep coming back to this preferable locale over significant time periods (Agam, 2020).

Brecciated flint types, which were often used at the site, especially for the production of bifaces and discoid cores, are often considered to be characteristic of the Campanian Mishash Formation (Kolodny, 1969), implying a non-local origin. However, Kolodny et al. (2005) suggest that the cracking, fragmentation and tearing involved in the formation of a brecciated texture are integral parts of the maturation of siliceous sediment into flint. If so, brecciated flint types might be associated with more than the Campanian Mishash Formation, and such a provenance identification should be treated cautiously.

The Campanian Mishash Formation sources closest to Jaljulia are located ~22 km south of the site, in the Ben-Shemen Forest. Additional Campanian Mishash sources are located some 30 km east to the site, in the Shekhem region (Sneh and Shaliv 2012). This would, theoretically, imply that such flint types could have been procured only from distant sources. However, as stated above, the eastern sections of Wadi Qana run by potential flint sources of the Campanian Mishash Formation. The wadi therefore could have potentially contained flint eroded from these eastern sources. In fact, a buliminid foraminifer, a fossil associated with Campanian Mishash flint (**Figure 7**), was observed in a thin section of a sample from the segment of Wadi Qana running through Horashim Forest (~1 km east of Jaljulia). Brecciated flint types were also observed within the ancient wadi found in Area A and in the current bed of Wadi Qana. Future work will attempt to determine whether these breccias are indeed Mishash or of some other origin, but the possibility remains that Campanian flint might have been procured locally from the channel bed and used extensively by the Jaljulia hominins.

As we can assume that the availability of flint at the paleo-landscape was one of the considerations encouraging hominins to settle there to begin with, it makes sense that most of the flint (but not necessarily all of it), would have come from the immediate vicinity of the site. Indeed, a preliminary classification of the Jaljulia flint types to their potential geologic origins, based on macroscopic and petrographic data, shows that all analyzed groups are dominated by locally available flint (**Table 5**), either from a Turonian origin, or from another, more distant source, which was secondarily deposited near Jaljulia. Interestingly, the proportions of such locally available flint are more accentuated among the bifaces (81.7%; n = 49), PCTs artifacts (82.3%; n = 51) and discoid cores (85.0%; n = 34), compared to the general sample and the prepared cores (general). While other types are present in lower proportions, the presence of some Campanian flint types which were not observed in local sources, as well as Cenomanian and Eocene flint types, is of note, indicating the transportation of flint from non-Turonian sources, either by streams, or by human agency. The closest Cenomanian sources (Eyal Formation) are located ~8 km north of Jaljulia. The closest Eocene sources, of the Timrat Formation, are located some 30 km east of Jaljulia. However, similarly to the Campanian eastern sources, these are located along the trajectory of Wadi Qana. Therefore, flint eroded from these sources could have been carried westwards by the river and closer to the site. On the other hand, as no Eocene flint was observed either in the current channel of the river, nor in the old channel found in Area A, we cannot rule out a scenario of the occasional long-distance procurement and transportation of these Eocene flint pieces to the site. Campanian flint types are more frequent in the general sample and the prepared cores (general) than among the other samples. Eocene flint, identified by the presence of macroscopically visible nummulites, is more common among the bifaces than in other categories (**Figure 3C**).

TABLE 5 | Potential geologic origins of the three Jaljulia samples. The Levallois, discoid and prepared core (general) groups include their products and CTEs.

Potential Geologic Origin	General Sample		Bifaces		Proto-Levallois		Discoid		Prepared (General)	
	Qty.	%	n.	%	n.	%	n.	%	n.	%
Turonian/locally available	272	66.8	49	81.7	51	82.3	34	85.0	80	72.7
Campanian	80	19.7	3	5.0	2	3.2	2	5.0	18	16.4
undetermined	41	10.1	3	5.0	6	9.7	1	2.5	7	6.4
Cenomanian	11	2.7	—	0.0	2	3.2	1	2.5	—	0.0
Eocene	3	0.7	5	8.3	1	1.6	2	5.0	5	4.5
Total Number of Artifacts per Group	**407**	**100.0%**	**60**	**100%**	**62**	**100%**	**40**	**100%**	**110**	**100%**

DISCUSSION

Selectivity in Flint Use

The presence of an old stream-bed in the south-eastern part of the site, as well as evidence for water activity throughout the geological sections of the site (Shemer et al., 2018, Accepted), suggest a landscape favourable for recurrent human occupations, as it was most probably rich in fresh water, vegetation, prey animals (which were attracted to the fresh water and plants), and rocks suitable for the production of stone tools (in stream deposits and near-by geological outcrops). This, in turn, led Late Acheulian humans to repeatedly visit the paleolandscape, as indicated by the wide-spread archaeological localities, which are assumed to be the result of repeated separate occupations over significant time periods throughout the late Lower Paleolithic period (Shemer, 2019; Shemer et al., 2022). The dominance of local flint types observed within the site's lithic assemblages should not, therefore, come as a surprise. Indeed, local lithic materials usually dominate Paleolithic assemblages (e.g., Ekshtain et al., 2017; Groucutt et al., 2017; McHenry and de la Torre, 2018; Agam, 2020).

While some argue that the dominance of local materials in archaeological lithic assemblages suggests that lithic materials were procured as a by-product during the performance of other subsistence activities (e.g., Binford, 1979; Kuhn, 1995; Ekshtain and Tryon, 2019; Shimelmitz et al., 2020), such a pattern may also imply that the high availability of desired lithic materials around a given locality, and their suitability for the manufacture of specific tools and blanks, played a main role in the original decision to repeatedly perform human activities at this location. Furthermore, locally available flint could have been procured by multiple short-distance task-specific ventures, so direct procurement of such materials is also a likely strategy (Agam, 2020, 2021). It is therefore our contention that the abundance of flint in Jaljulia and its surroundings, and its suitability for the production of the various stone tools used by the Jaljulia inhabitants, played a role in the decision to settle and resettle at the place. Clearly, other subsistence resources, such as water, edible plants and animal prey, abundantly available at the locale, further enhanced its attractiveness.

Moreover, the analyzed samples demonstrate some extent of selectivity in flint allocation towards specific knapping trajectories. Some flint types are more frequently applied in the manufacture of distinct artifact categories than in others. Fine-textured, homogenous flint types, for example, were preferred for the production of cores and Cores-on-Flakes. Brecciated flint types, on the other hand, were especially dominant among the bifaces and discoid cores. This also should not come as a surprise, given that selectivity in stone types use has been repeatedly demonstrated in Levantine Lower Paleolithic contexts (e.g., Bar-Yosef and Goren-Inbar, 1993; Saragusti and Goren-Inbar, 2001; Wilson et al., 2016; Agam, 2020; Assaf and Preysler, 2022), as well as in older contexts in Arica (e.g., Braun et al., 2008a,b; Goldman-Neuman and Hovers, 2012; Reeves et al., 2021). Such selectivity could have been influenced by a wide range of considerations, including mechanical factors, size preferences, and efficiency-related aspects (e.g., availability, accessibility, abundance, endurance etc.). However, considerations extending beyond cost-benefit could also be accounted for, such as cultural, cosmological and/or aesthetic aspects (see discussion in Agam, 2020). The ethnographic record further demonstrates the existence of additional non-utilitarian considerations in the selection of specific stone-types for distinct production trajectories (e.g., Gould and Saggers, 1985; Mcbryde, 1986; Brumm, 2010; Arthur, 2018; Reimer, 2018), stressing the complexity in straight-forwardly inferring lithic-related decision-making during prehistory. Such considerations have been suggested to be relevant in Paleolithic contexts as well (e.g., Moncel et al., 2012; Radovčić et al., 2016; Assaf, 2018; Efrati et al., 2019; Assaf and Romagnoli, 2021; Efrati, 2021; Peresani et al., 2021). The inhabitants of Jaljulia might also have had preferences related to specific visual attributes of the flint types and/or meaning attached to such things as the place of origin of the flint, giving it some significance in their relationships with the landscape around them.

The consistency observed in stone-type use and selectivity between the assemblages of Areas B and D implies similar considerations in flint procurement and use throughout space and time. This pattern becomes even more significant if human activities at the two areas were indeed as distant in time as the chronometric results suggest. This may suggest that knowledge was transmitted and shared between individuals, and possibly between groups, concerning the distribution of flint around the site, as well as concerning the suitability of specific flint types for the production of specific tools and blanks. Further studies of the other localities at the site may imply whether similar considerations in flint selectivity and use were actually practiced throughout the extensive paleo-landscape and the long record of human activity at the locale, which was supposedly spread over hundreds of thousands of years. Even if mostly practical considerations guided flint selectivity at the site, the persistence of such behavioral traits for such an extended duration may stand as another demonstration of the successful mode of adaptation practiced during Acheulian times, notably manifested previously in the continuous application of technological and economic strategies throughout the Lower Paleolithic (e.g., Rabinovich and Biton, 2011; Sharon et al., 2011; Finkel and Barkai, 2018).

The results presented above therefore indicate a profound familiarity of early humans with the geologic resources surrounding them, and understanding of the significance of the different traits of the flint available (either morphological, mechanical, visual, or any combination of the three). Moreover, it shows that attention and effort were put into the acquisition of specific lithic materials for the production of specific tools and blanks. This further implies that the idea that the use of local lithic materials reflects a lack of preference, as well as the integration of lithic procurement into other subsistence activities, should be reconsidered.

Possible Implications for the Emergence of Prepared Core Technologies

While the first emergence and adoption of PCTs and the technological and conceptual roots of the Levallois production seem to be found in the Acheulian, the technological origins of the Levallois production are still disputed. It has been suggested, for example, that earlier core technologies served as a basis for its emergence (Tryon et al., 2005; Sharon, 2009; Johnson and McBrearty 2012; Adler et al., 2014). These proposals support a scenario of convergence rather than “a single origin” hypothesis (Adler et al., 2014). Others, on the other hand, view Acheulian handaxes and cleavers as the basis for the emergence of the Levallois production. There are, for example, cases of handaxes with later preferential flake scars, taking advantage of the convexities of the handaxes, implying a conceptual and technological links between handaxes and Levallois technologies (DeBono and Goren-Inbar, 2001; Marder et al., 2006; Goren-Inbar, 2011; Shimelmitz, 2015; Rosenberg-Yefet and Barkai, 2019). Rolland (1995) proposed that the skill involved in the production of handaxes may have led to the discovery of the Levallois production. Tryon et al. (2005) suggested that the Levallois production was developed from previous Acheulian lithic traditions, namely large blanks used for the manufacture of handaxes and cleavers. While some have suggested a scenario of an unintentional discovery of the Levallois production through the manufacture of bifaces (Rolland, 1995; Shipton et al., 2013), the presence of preparation scars on bifaces with preferential removals before the removal of the predetermined flakes testifies for intentional actions rather than knapping mistakes (Rosenberg-Yefet et al., 2021).

In the case of Jaljulia, Rosenberg-Yefet et al. (2021) demonstrated that handaxes from the site (and from the Late Acheulian site Revadim) were repeatedly recycled for the production of preferential flakes. Following this, it was proposed that the two technological trajectories are conceptually linked, possibly demonstrating the existence of cumulative culture, or “the Ratcheting Effect”, first defined by Tomasello (1999). This means that high-fidelity social learning mechanisms (i.e., involving teaching and/or imitation) were used to establish beneficial improvements in existing technologies, leading to the formation of new complex technological innovations that could not be invented by a single individual.

The results presented above show that there are similarities between the flint types and groups of flint types used for the production of bifaces and discoid cores, implying a possible shared set of properties applied in the selection of flint types for the manufacture of the two trajectories. Especially interesting are the high proportions of brecciated flint types in both groups, possibly related to the large packages they tend to be found in, and/or to the possible durability of the artifacts produced from such nodules (Agam et al., 2020). On the other hand, the frequencies of these brecciated flint types and groups of flint types among the Proto-Levallois cores and prepared cores (general) do not exceed those observed in the general sample. Rather, homogenous flint types were found to be more common among these two groups. Homogenous flint types are also more frequent among Cores-on-Flakes. It is therefore possible that homogenous lithic materials are a better fit in cases in which a greater degree of control over the end-product is desired, as well as the need to produce sharper edges (Agam and Barkai, 2018). Interestingly, it has been demonstrated that in both Acheulian and MSA African sites Levallois artifacts tend to be made of fine-grained raw materials (Tryon et al., 2005), further underlining the significance of the mechanical properties of the lithic material used for Levallois production.

Thus, it seems that there are technological and conceptual links in flint selectivity and use between PCTs and both flake and biface technologies at Jaljulia. We therefore support the idea of Rosenberg-Yefet et al. (2021), suggesting that it would be more appropriate to speak in terms of multiple technological origins of the Levallois production in the Acheulian, rather than a single origin. As part of the concept of cumulative culture, technological knowledge could have been accumulated through time from various Acheulian lithic trajectories, and combined to create a novel, innovative technological trajectory. The benefit gained from using a circumferential bifacial ridge could have been ‘borrowed’ from the biface production technology, while the technological adjustment of using homogenous, fine-textured lithic materials when looking for a greater control over shape and size could have been ‘borrowed’ from flake production technologies, including “regular” cores and Cores-on-Flakes.

The proposed process suggests the existence of knowledge transmission mechanisms, either ones reflecting high fidelity social learning (involving teaching and/or imitation), or, alternatively, low fidelity social learning, such as stimulus enhancement or local enhancement (Tennie et al., 2016). While both options are valid, we view the former as the more likely. The Proto-Levallois products observed in Jaljulia demonstrate a multi-staged technological procedure, which demands a high degree of understanding, planning depth and technological know-how (Rosenberg-Yefet et al., 2021). Furthermore, the knowledge transmission suggested above concerning the distribution of suitable flint sources and the suitability of specific flint types or specific tasks also require high-fidelity social learning. Therefore, and as it has already been proposed that Acheulian populations transmitted knowledge and technological know-how using verbal communication (Goren-Inbar, 2011), it is our contention that high fidelity social learning mechanisms were involved in the application of PCTs observed at Jaljulia.

Finally, the Proto-Levallois artifacts has demonstrated a gradual process of development at the end of the Lower Paleolithic of Africa, Europe, the Levant and the Caucasus, towards a sort of proto-Levallois technology (Rosenberg-Yefet et al., 2021, and see references therein). This further accentuates the accumulation of technological innovations, and may be considered to be a demonstration of the Ratcheting Effect of cumulative culture.

CONCLUSION

This study evaluates patterns of flint procurement and exploitation during the Late Acheulian of the Levant, at the site of Jaljulia. It further compares these patterns between four groups of samples: a general sample, consisting of all typo-technological categories, a sample of bifaces, a sample of "regular" cores, and PCT-related artifacts, including proto-Levallois cores, prepared cores (general) and discoid cores. Our results show that locally available flint types were commonly used at the site, suggesting that their high availability played a role in the decision to locate at the site, in addition to other resources, which further increased the attractiveness of the local paleolandscape. Still, while local flint types were commonly used, a clear selectivity in flint type exploitation was observed, showing that specific flint types were preferred for the production of specific blanks, due to morphological, mechanical or visual considerations, or any combination of these factors.

Our results suggest that PCTs and specifically the Proto-Levallois production procedure did not originate from one single technological trajectory. Rather, it probably incorporated knowledge that was acquired in a long process from several technological trajectories, including biface production, "regular" cores, and Cores-on-Flakes. From each such trajectory, the traits suited for the relevant needs were "burrowed", taking into account technological traits of known technologies, as well as the suitability of specific flint types for the production of the desired blanks. The knowledge gathered was used to develop a novel, innovative technological trajectory, which was directed towards the manufacture of blanks of predetermined size and shape. This novel technology was most likely transmitted time and again between individuals, gradually adjusting it to produce improved end-products. These improvements included, most likely, the use of circumferential, bifacially shaped ridges, and the more pronounced exploitation of fine-textured, homogenous flint types, all for a better control over the shape and size of the end-product. We see these conclusions as additional support for our view of the Proto-Levallois production of the Late Acheulian as a demonstration of cumulative culture, and the existence of high-fidelity social learning mechanisms already during Lower Paleolithic times.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

AA is the lead author, with major contributions from TR-Y, LW, MS, and RB. AA, TR-Y, and RB designed the study; AA performed the data analysis and wrote the paper; TR-Y conducted the typo-technological analysis; AA and LW performed the geologic surveys and the petrographic analysis; MS excavated the site of Jaljulia; AA, LW, and RB edited the manuscript; all authors commented on and contributed to the manuscript.

FUNDING

This research is supported by the joint UGC–ISF Research Grant (Israel-India program) entitled "The First Global Culture: Lower Paleolithic Acheulean Adaptations at the Two Ends of Asia" (2712/16), and by The Irene Levi Sala CARE Archaeological Foundation (182).

ACKNOWLEDGMENTS

We thank Sasha Flit (TAU) for the photographs used in this article. We also thank the reviewers of this article for their insightful comments and suggestions.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2022.858032/full#supplementary-material

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ORIGINAL RESEARCH
published: 08 June 2022
doi: 10.3389/feart.2022.917207

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Acheulean Diversity in Britain (MIS 15-MIS11): From the Standardization to the Regionalization of Technology

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OPEN ACCESS

Edited by:
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Specialty section:
This article was submitted to Quaternary Science, Geomorphology and Paleoenvironment, a section of the journal Frontiers in Earth Science

Received: *10 April 2022*
Accepted: *19 May 2022*
Published: *08 June 2022*

Citation:
García-Medrano P, Shipton C, White M and Ashton N (2022) Acheulean Diversity in Britain (MIS 15-MIS11): From the Standardization to the Regionalization of Technology. Front. Earth Sci. 10:917207. doi: 10.3389/feart.2022.917207

The appearance of the Acheulean and the production of new bifacial tools marked a revolution in human behavior. The use of longer and complex operative chains, with centripetal and recurrent knapping, adapted to different raw materials, created long useful edges, converging in a functional distal end. How and why these handaxes vary has been the subject of intense debates. Britain provides a clearly defined region at the edge of the hominin occupied world for discussing variation in Acheulean assemblages. The environmental changes from MIS 15 to MIS 11 are significant in understanding population change, with probable breaks in evidence during MIS 14 and MIS 12, followed by several sites during the long stable climate of MIS11c. In this latter period, different Acheulean technological expressions appear to coexist in Britain. This paper draws together different studies, combining technology and geometric morphometrics to analyze handaxes from six British sites: Brandon Fields, Boxgrove (Q1B), High Lodge, Hitchin, Swanscombe (UMG), and Elveden. Compared to the earlier Acheulean of MIS 15, the assemblages of MIS 13 show increased standardization and the use of soft hammer percussion for thinning mid-sections and butts of tools, or sharpening tips through tranchet removals. Although there is regional population discontinuity through MIS12 there is no evidence of a marked change in technology after this glacial period. Rather, there is a development towards more intense shaping with the same underlying techniques, but with flexibility in imposed handaxe form. From MIS11 there appear to be distinctive localized traditions of manufacture, which suggest that a recognition of place and territories had developed by this time. These are expressed over medium time-scales of several thousand years and have significance for how we view cultural expression and transmission.

Keywords: middle pleistocene, britain, acheulean, technology, handaxes, geometric morphometrics (GM)

INTRODUCTION

The linked concepts of social learning, knowledge transfer and cultural transmission have long been recognized as important areas of early human research, particularly in relation to the development of complex technologies and cumulative culture (e.g., Mithen, 1994; Tomasello, 1999; Boyd et al., 2011; Pradhan et al., 2012; Dean et al., 2014; Henrich, 2015; Henrich and Tennie, 2017; Pargeter et al., 2019; Stout et al., 2019). But attempts to demonstrate the role of cumulative culture (Rosenberg-Yefet et al., 2021), and understanding the detailed mechanics of how they operate, have often been hindered by the large geographies and long timescales of the Lower Paleolithic record. The period is populated by short-term glimpses of human behavior, usually represented by lithic evidence that is scattered through space and time. Although this enables detailed behavioral insights or broad narratives of technological development, what is often missing between these short and long timescales is an understanding of how culture develops, is structured and persists at the millennial scale of several thousand years. In essence how did societies operate through multi-generational timescales in the Lower Paleolithic?

For Europe, questions of cultural transmission are particularly acute, as long-term cyclical changes in climates and environments led to ebbs and flows of population either between north and south or potentially with depopulation of the entire continent (Roebroeks, 2006; Dennell at al., 2011; Moncel et al., 2015). Often characterized as the 'source and sink' model, questions still remain about the boundaries between these zones, and whether cultural transmission was maintained throughout the Middle Pleistocene within Europe, or was dependent on source areas beyond.

Britain can be used as a laboratory for beginning to understand these concepts at the medium timescale. Middle Pleistocene research in Britain over the past 30 years has created a robust geological framework within which the abundant archaeological record can be placed (Bridgland, 1994; Bowen, 1999; Schreve, 2001; Penkman et al., 2011; Preece and Parfitt, 2012; Lewis et al., 2021). Work has highlighted the discontinuous nature of the record, which was due in part to successive glaciations, but also to Britain's position as a cul-de-sac of Eurasia, tenuously linked to the main continent by a narrow isthmus of optimally 150 km wide during warm periods (Preece, 1995; White and Schreve, 2000; Hijma et al., 2012; Ashton et al., 2016; Ashton and Davis 2021). This specific geography appears to have led to a series of short-term population incursions into Britain with a diverse array of material culture manifested in simple core and flake assemblages and those with distinctive handaxe forms. Due to the resolution of the geological framework, these population incursions can sometimes be attributed to isotope substages, and for some MIS 11 sites attributed to pollen zones of a few thousand years within substages (Ashton et al., 2016; Davis and Ashton 2019). This detailed record enables interrogation of the meaning behind handaxe form at the medium timescale.

Variation in handaxe form in Britain was recognized from the inception of the subject (Evans 1872, 1897). But it was Roe (1968), building on the metrical work of Bordes (1961), who provided a structure within which site assemblages could be categorized, identifying seven major Groups with several sub-groups, based on linear dimension ratios. Through the following decades the groups were hard to interpret due to poor chronological resolution, but as dating has improved over the last 30 years work has refocused on Roe's original groups (Bridgland and White, 2014, 2015; White, 2015; White et al., 2018). These papers have taken Roe's original analyses with the addition of new sites, and suggest that there is chronological patterning in the British handaxe record. In parallel, a further series of papers have put forward the notion of a series of population incursions with differences in material culture, including those with distinctive handaxe forms (Ashton, 2016; Davis and Ashton 2019; Davis et al., 2021a; Ashton and Davis 2021).

All these studies used either published data, or standard metrical analyses, but over the last few years there has been increasing use of 3D morphometrics for analyzing variation in handaxe form (Lycett et al., 2006; Archer and Braun, 2010; Shipton, 2013; Shipton and Clarkson, 2015a; Herzlinger et al., 2017; Hoggard et al., 2019). This method was at the heart of the Marie-Curie funded Western European Acheulean Project (WEAP), which developed a unified technological analysis of handaxes in combination with 3D morphometrics (see below). These methods have been used in the current work drawing on analyses undertaken by Shipton and White (2020) in combination with those from the British sites studied for WEAP (García-Medrano et al., 2019; García-Medrano et al., 2020, submitted).

The purpose of this paper is to use handaxes from six key British Middle Pleistocene sites that span the period from MIS 15 through to MIS 11 to answer the following questions:

1 Are the distinctions in handaxe form that have been identified in previous studies, supported by the current analyses using the WEAP method?
2 Are there chronological patterns in the data between the different isotope stages?
3 Are there spatial patterns within any of the isotope stages?

The results will be used to examine long-term developments in technology between MIS 15, 13, and 11 of whether there are underlying trends that suggest elements of continuity in northern Europe, albeit outside Britain, or whether there are abrupt changes in technology between the isotope stages, indicative of much more southerly source areas for incoming populations. For MIS 13 and 11, the results will be used to show whether there are regional differences or similarities within these isotope stages, and what this may mean in terms of population and group cultural dynamics.

MATERIALS AND METHODS

Archaeological Contexts

The six British sites that have been analyzed for this paper consist of Brandon Fields (MIS 15), Boxgrove and High Lodge (both MIS 13), and Elveden, Swanscombe and Hitchin (all attributed to the long, warm MIS 11c substage). The sites were selected because of the good resolution of their dating. The combination of glacial history, its relationship with terrace stratigraphy, good preservation of biological remains, and the wide deployment of aminostratigraphy enables correlation between sites and the Marine Isotope record (Ashton, 2016). They vary from assemblages collected in the late 19^{th} century (Brandon Fields), to those more recently excavated (Boxgrove). They are all open-air sites from alluvial and lacustrine contexts and therefore inevitably are samples of landscapes and subject to a variety of taphonomic processes. Although the methods of recovery vary at the different sites, the inclusion of cores and flakes in the collected assemblages reflects thorough recovery, and not just selection of the finer pieces. As the study is focused on handaxes, the collected assemblages are likely to be representative of the wider handaxe populations. For this study, some of the assemblages were sub-sampled. This was achieved through a visual inspection of the entire assemblage with selection of consecutive boxes that appeared to be representative, rejecting incomplete handaxes. Brief descriptions of the sites are given below with references for more detailed information about the sites.

Brandon Fields is now an area of undulating hollows that mark former gravel pits on a hilltop to the south-west of Brandon, Suffolk. Handaxes and other artefacts were collected here from the late 1860s most notably by James Flower, who gave a clear description of the location and geology (Flower 1869; Evans 1872; Evans 1897). Recent fieldwork has confirmed the original descriptions, which interprets the gravel as being from the Timworth Terrace of the Bytham River dating to MIS 14 and that most of the assemblage derives from MIS 15 land-surfaces (Davis et al., 2021a; Lewis et al., 2021). The British Museum holds 148 of the handaxes, which consist of two condition types. Around 85% are rather crude in manufacture, elongated, thick, relatively abraded, and generally stained. The remainder are generally ovate in form, fresher condition and exhibit more patination. Although an absolute split between the two assemblage types is difficult, 50 were sampled for this study, which generally adhere to the first group of cruder forms.

High Lodge is also a River Bytham site, just 10 km south of Brandon Fields. It is situated in a disused clay pit with the first artefacts discovered in the 1870s. The clays yielded a core, flake and scraper industry, while overlying sands provided an assemblage of handaxes (Evans, 1872; Whitaker et al., 1891; Marr, 1921). Extensive excavation by the British Museum (1962–68 and 1988) established the geology and archaeological contexts of the site (Ashton et al., 1992; Lewis et al., 2021). The clays (Bed C) and overlying sands (Bed E) are floodplain sediments of the Bytham River dating to MIS 13, which were subglacially deformed during the Anglian glaciation (MIS 12). For this study 32 handaxes from Bed E were recorded.

Boxgrove is located above the Sussex coastal plain in the former Eartham Quarry that revealed a sequence of marine, freshwater and terrestrial sediments that formed beneath a marine-cut chalk cliff (Roberts and Parfitt, 1999; Pope et al., 2020). The site dates to late MIS 13 based on mammalian biostratigraphy. The chalk provided abundant flint raw materials for the archaeological horizons, which consist of extensive lithic scatters associated with butchered mammal remains. The main concentration of 414 handaxes was excavated from around the Q1B watering hole, from which 50 were recorded for the present paper.

Elveden (Suffolk) is a disused clay pit from which handaxes were recovered in the early 20th century, with more formal excavation in 1937 (Paterson and Fagg, 1940). The most recent fieldwork was from 1995 to 1999, which revealed that fine-grained lacustrine and fluvial sediments infill a small basin and date to the first half of the Hoxnian interglacial (MIS 11c; Ashton et al., 2005). The main handaxe assemblage was collected in the early 20th century with additional material from the two excavations, the latter being concentrated around the edges of the basin and likely dating to the peak interglacial (Hoxnian pollen zones IIc-III; Davis and Ashton, 2019). Adjacent chalk provided a nearby source of flint, while refitting and the fresh condition of the artefacts indicates that most of the assemblages are in primary context. In total 80 handaxes have been recorded from the site and held in several different museums. For this research the 29 complete handaxes in the British Museum collection were studied, including three from the 1990s excavations.

Swanscombe (Barnfield Pit) is located on the Orsett Heath terrace of the River Thames in Kent, where fluvial sediments are attributed to the Hoxnian interglacial (MIS 11c; Smith and Dewey, 1913; Ovey, 1964; Wymer, 1968; Conway et al., 1996). The Lower Gravel and Lower Loam contain non-handaxe assemblages and date to the first half of the interglacial (Hoxnian pollen zones I and II), while handaxe assemblages have been recovered from the Lower Middle Gravel and the Upper Middle Gravel, which date to the peak interglacial (Hoxnian pollen zones late II and III). For this study, we sampled 50 handaxes from the Wymer 1950s excavations of the Upper Middle Gravel, in combination 34 handaxes from undifferentiated Middle Gravels, collected by Marston in the middle decades of the 20th century. Both collections are held at the British Museum. The assemblages are in secondary context, but were probably derived from the nearby floodplain of the river, using local flint gravels as the source for raw material.

Hitchin. A series of clay pits around the town of Hitchin were exploited in the late 19th and early 20th centuries, from which handaxe assemblages were collected (Reid, 1897; Boreham and Gibbard, 1995). Most reports suggest that lacustrine sediments infill a basin or series of basins above Anglian till and glacial gravels. The stratigraphic position and palynology from the clays suggest that they date to the first half of the Hoxnian interglacial (MIS 11c). A thick sequence of overlying "brickearth" has been interpreted as a combination of colluvial, fluvial and aeolian deposits (Boreham and Gibbard, 1995). Over 60 handaxes were collected in the late 19th and early 20th centuries, many from a gravelly loam at the base of the 'brickearth' (Reid, 1897), although after Reid's visit others were found in the Lake Beds alongside interglacial mammalian remains (Reid, 1898, p18, footnote) while a photograph taken in 1885 seems to put the find location of at least one handaxe to within the lacustrine sediments (Bloom, 1934, 39). Recent works (White et al., 2019; Shipton and White 2020) have suggested that two separate assemblages may be combined in the Hitchin sample, perhaps belonging to different parts of the same sub-stage (as found at Foxhall Road, Ipswich) or different sub-stages (as found at Swanscombe, Kent).

Methods

Each handaxe was analyzed from two points of view: as a single unit, and as the sum of three separately analyzed morpho-functional parts; the tip, mid-section, and butt (**Table 1**) (García-Medrano et al., 2020). The division of each tool into three parts is based on the metrical distinction of the distal part at 1/5 of length, and the proximal part as 4/5 of length from the tip

TABLE 1 | Technological features and linear measurements considered to analyze LCT according to the WEAP Method.

WEAP method: Technological Features LCT as one unit		
Variable	**Categories**	**Description**
Raw material	Type	Flint, chert, quartzite, quartz, limestone, and other metamorphic rocks
Blank type	Blocks	Broken from bedrock
	Nodules	Eroded from bedrock
	Cobbles	From river gravel
	Flakes	Detached from cobbles/nodules/blocks
Number of faces	Unifacial	Only one shaped face
	Bifacial	Two shaped faces
	Trifacial	Three shaped faces
Cortex localization	Tip	Cortex only on tip
	Mid	Cortex on mid-part
	Butt	Cortex on butt
	All	Cortex along the whole piece
Edge delineation	Straight	In profile view
	Sinuous	
	Curved	
Symmetry	SIM	Symmetric hemispheres
	NSIM	Asymmetric hemispheres
Number of scars	(N)	Counted per face
LCT for each morpho-functional part (tip, mid and butt)		
Variable	**Categories**	**Description**
Hammer used	Hard	Deep bulbar impressions, deep effect of scars on edge
	Soft	Minimal bulbar impressions, marginal effect of scars on edge
	Combined	Combination of both
Presence of Cortex	%	
Removal Series *Add as many as needed	1	One removal series
	2	Two removal series
	3 . . .	Three removal series (or more)
	Final Retouch	Could be a removal series by itself
	Combined	The combination of these series
Depth scars on edge	Deep	Generating denticulate edges
	Marginal	Creating continuous edges
Invasiveness (scars on tool's surface) *analyse each series of removals	Non-invasive	Removals travelling <50% of distance to midline
	Invasive	Removals affecting ≥50% of piece
Final Retouch	Non-invasive	Removals close to the edge
	Invasive	Removals affecting ≥50% of piece
	Specific types	e.g. *Tranchet*, Shallow retouch
Type of shaping	General	According to the rest of tool's shaping strategy
	Specific	In a different way (e.g. combination of different series, or with different depth or invasiveness)
	Final Retouch	e.g. *tranchet* removals or shallow retouch
LCT linear measurements and indices		
Length (L)		
Maximum width (m)		
Maximum Thickness (e)		
Width at middle Length (n)		
Distal width (B1)		
Proximal width (B2)		
Distal Thickness (T1)		
*Elongation Index (L/m)		
*Refinement Index (m/e)		

(Roe 1968). As a single unit, each tool can be defined by a combination of features that make it unique: material and blank type, facial working, edge delineation, bifacial and bilateral symmetry, and number of scars. The technological features considered on the three tool sections are type of hammer, number of removal series, depth of scars on edges, invasiveness of scars on a tool's surface, type of shaping and any patina variation.

Together with the technological descriptions, measurements were the basis of Bordes' handaxe morphological types ("triangulaires", "subtriangulaires", "cordiformes", discoid, ovate, and "limandes") according to two main criteria: length against width, width against thickness (Bordes, 1961). However, the boundaries between the categories were sometimes imprecise, leading Roe (1968) to include three new measures: distal width (B1), proximal width (B2) and distal thickness (T1), to distinguish three shapes: pointed, ovate and cleaver-type tools. We retain all these measures to describe the tools, and compare the results with the morphological and technical features such as reduction intensity. The measurements have also been used to produce ratios to enhance handaxe description (Bordes 1961; Roe 1968, 1994). Elongation is given as length/width with values > 1.5 described as elongated. Refinement is measured by width/thickness with refined handaxes having values > 2.35.

This large set of technological features was combined by applying Correspondence Analysis (CA) to identify the differences and similarities of handaxes and cleavers as both complete tools and as three parts of a tool (tip, mid-section, and butt). The analysis also compared raw materials and types of blank. The Components 1, 2, and 3 were also explored with the Kruskal–Wallis non-parametric test to determine whether or not there are statistically significant differences between the medians of multiple assemblages, using PAST 3.14 software.

In addition to the technological analysis, we applied geometric morphometrics on 3D models to analyse tool shape variation. Tools were scanned both using DLP projector laser scanner and Flexscan software v.3.3.5.8. (LMI technologies, Canada) transferred from the Fragmented Heritage Project (University of Bradford), or a NextEngine and ScanStudio software. The 3D models were processed using the AGMT3-D software v.3.1 (Herzlinger and Grosman, 2018; Herzlinger and Goren-Inbar, 2020). This is a data-acquisition procedure for automatically positioning handaxe 3D models in space and fitting them with grids of 3D semi-landmarks. Each point of the grid consists of two semi-landmarks, one placed on each face of the artefact, so that a 50 × 50 grid provides 5,000 landmarks. This protocol provides a list of landmarks that accurately express the artefact's volumetric configuration. It also provides a number of analytical tools and procedures that enable data processing and statistical analysis (Herzlinger and Grosman, 2018).

By examining the morphological deformations and XY plots of specimens from the PCA scatters, it is possible to interpret shape variation by itself and compare the different tools within a site or between different sites. In addition, the derived principal component scores allow for the application of other quantitative tests of multivariate equality of means between the groups (Costa, 2010; Herzlinger and Grosman, 2018; Herzlinger and Goren-Inbar, 2020). Specific multivariate analysis of variance (MANOVA) of the first 10 PCs helps to evaluate whether the differences between multiple groups are statistically significant or not. The alpha level for significance was determined as $p < 0.05$.

The latest version of this software (v.3.1) also offers different quantitative approaches to the analysis of specific variations in shape. First, we used the surface analysis and volume data to apply a quantitative approach to reduction intensity. The Scar Density Index (SDI, Clarkson, 2013; Shipton and Clarkson, 2015a, Shipton and Clarkson, 2015b) has been defined as the number of flake scars (greater than 10 mm in maximum dimension) divided by the surface area (in^2). In addition, the landmark data was used to calculate the degree of deviation from perfect bilateral and bifacial symmetries, as well as the edge section regularity of each item in the sample (Herzlinger and Goren-Inbar, 2020). The bilateral symmetry analysis was conducted by measuring the mean 3D Euclidean distance between a mirror reflection of the landmarks placed on one lateral half of each object and the corresponding landmarks on the other half. The same procedure was performed for bifacial symmetry, but on the two opposing faces. In a perfect bilaterally or bifacially symmetrical object, the value of these indices will be 0, with increasing values indicating less symmetrical objects.

TABLE 2 | Total number of instruments by type of blank (Cobble/nodule, Flake and Unknown) and sites (BOX, Boxgrove; BF, Brandon Fields; ELV, Elveden; HL, High Lodge; HN, Hitchin; SW, Swanscombe).

	Cobble/ Nodule		Flake		Unknown		Total
	(N)	%	(N)	%	(N)	%	
BOX	17	19.77	28	32.56	41	47.67	**86**
BF	12	24.00	14	28.00	24	48.00	**50**
ELV	—	—	14	48.00	15	51.72	**29**
HL	—	—	12	37.50	20	62.50	**32**
HN	6	20.00	9	30.00	15	50.00	**30**
SW	24	28.57	27	32.14	33	39.29	**84**
TOTAL	59	18.97	103	33.12	148	47.59	**311**

Bold values are total number of instruments per site.

RESULTS

Our sample comprises 311 flint handaxes from six archaeological sites, dated from MIS 15 to MIS 11c. For blank types, 18.97% of them are made on cobbles/nodules, 33.12% on flakes and in 47.59% of cases the intensity of shaping precluded blank type identification (**Table 2**).

Metrically, our sample is standard with respect to the elongation of tools, but has a high inter-site variability with

TABLE 3 | Intra-assemblage shape variability analysis (mean multidimensional Euclidean distance of all artefacts from its centroid) and distribution of relative shape variability across dimensions of **Figure 2**.

			% Variability Caused by		
	(n)	Shape variability	x (Width)	y (Length)	z (Thickness)
BF	48	7.82	48.41	3.06	48.53
BOX	87	4.88	54.10	3.86	42.04
HL	32	5.42	63.10	5.38	31.52
ELV	29	7.80	56.85	5.08	38.07
HN	29	6.58	53.34	2.26	44.41
SW	85	8.04	49.27	2.39	48.34
MIS15	48	7.82	48.41	3.06	48.53
MIS13	119	5.05	56.62	4.30	39.08
MIS11c	143	8.02	51.63	2.81	45.56

Abbreviations: BF, Brandon Fields; BOX, Boxgrove; HL, High Lodge; ELV, Elveden; HN; Hitchin, SW, Swanscombe.

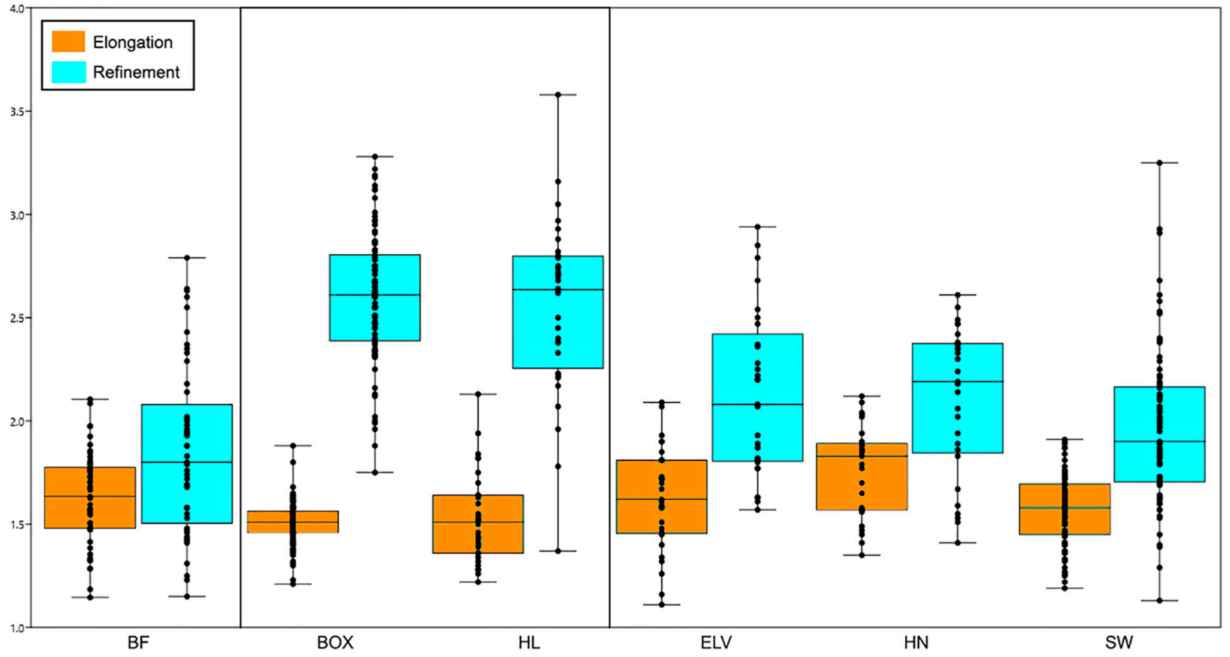

FIGURE 1 | Boxplot with jitter of elongation and refinement values per sites. Abbreviations: BF, Brandon Fields; BOX, Boxgrove; HL, High Lodge; ELV, Elveden; HN; Hitchin, SW, Swanscombe.

respect to the refinement (SOM **Table 1**). In fact, the morphological variation of the artefacts is mostly affected by their width and thickness (**Table 3**). **Figure 1** explores these two indices by site and MIS. Boxgrove and High Lodge display a similar pattern with the most refined and least elongated. The MIS 15 site of Brandon Fields presents a lower median refinement value than any of the younger sites. MIS 11c sites reflect a clear common pattern, different from MIS 13 locations but similar to each other, with higher elongation and lower refinement values than MIS 13.

Principal Component Analysis on 310 3D models produced 309 principal components (PCs) with 90.37% of the variability explained by the first 28 PCs. PC1 and PC2 together describe more than the 40% of the variability, which from positive to negative values represent for PC1 (27.71%) thin oval to thick pointed shapes, and for PC2 (12.34%) refined to thicker tools (**Figure 2**). MIS 13 sites are the least variable assemblages (**Table 3**), both Boxgrove and High Lodge containing more oval and refined shapes. Handaxes from Swanscombe are the most pointed and thickest tools. Wilcoxon Rank-sum test on interpoint distances between Boxgrove and Swanscombe indicate the morphometrical differences between them are statistically significant (ranksum = 20,638; n1 = 87; n2 = 85; $p < 0.01$). MIS 11c sites present much greater variability. Whereas Elveden's mean shape is located at the centre of the graph, with a clear tendency to oval shapes, and the widest point closer to the middle of the tools, Hitchin and Swanscombe present more pointed shapes with their widest point towards the butt. The differences between these MIS 11 sites are statistically different (ranksum = 10,452; n1 = 29; n2 = 85; $p < 0.01$).

With respect to symmetry (**Table 4**), the MIS 13 sites have lower mean values than other assemblages, something that may be related to the use of long shaping sequences, the degree of invasiveness of their removals, the use of soft hammer percussion (organic materials or potentially soft stone), with particular care to the edges. MIS 11c tools present the major irregularity. And in spite of the similarities between MIS 13 sites and the Elveden shaping strategies, Elveden handaxes show 300% more irregularity in their profiles than Boxgrove. This however is entirely the consequence of the deliberately imposed sinuous, twisted-profile shape which characterize this site (**Figure 3**).

The question remains as to whether their morphometrical differences are the consequence of different technological traditions and whether these morphological contrasts are accompanied by changes in the underlying technologies? To address these questions we have combined all the technological features (**Table 1**) in a Correspondence Analysis (**Figure 4**). Components 1, 2, and 3 explain 88.84% of the variability of our samples, and the contribution of each one of them varies depending on the site (**Figure 4C**).

MIS 13 sites occur in the same quadrants and represent the longest reduction sequences, with a strong consistency of approach in the technological strategies applied to the three parts of the tools (tip, mid-part, and butt). They are mainly shaped using two removal series, plus final retouch, with soft hammer percussion. Usually, the first series is very invasive and the second one, non-invasive. Removals have a limited effect on edges, which are straight and sinuous in profile view, with symmetric and, in a minor proportion, plano-convex silhouettes.

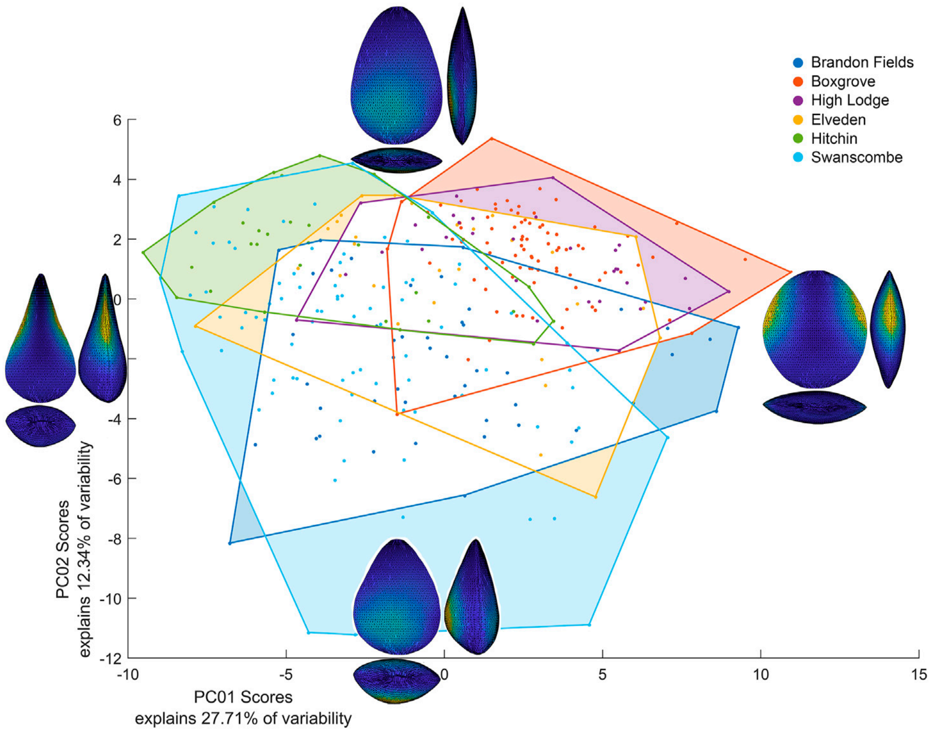

FIGURE 2 | Geometric morphometrics: PCA on handaxe 3D models by sites. Illustrations show hypothetical objects situated at the extremities of each principal component, reflecting the shape trend it represents. Convex hulls represents the scatter plot limits on each site. The white area is the overlapped area.

Our MIS 15 site, Brandon Fields, plots outside the range of MIS 13 sites for most components. This is due to a mix of features, shorter sequences on cobbles combined with longer shaping ones on unknown blanks; when examined at the level of technological features by handaxe zone (**Figures 5**, **6**), mid-parts and butts are mainly shaped by only one removal series plus non-invasive final retouch focused on edges.

The MIS11c handaxes are more variably distributed in the graphs. Elveden and Swanscombe have similar values for components 1 and 3, but differ on component 2 (**Figure 4**). This likely reflects cortical presence and the tip shaping strategy. Elveden tips are shaped with final retouch in more than 65% of cases, removing previous technological information. In 40% of implements, this corresponds with tranchet removals. Swanscombe presents a high proportion of residual cortex, concentrated on butts and mid-parts. Their tips are shaped in a variety of ways, combining 1 and 2 removal series with invasive and non-invasive final retouch. Tranchet blows are scarce. The common ground between Elveden and Swanscombe is the mid and butt shaping strategy. Mid-parts are made with a first invasive removal series combined in some cases with a non-invasive one. The butts are shaped with only one removal series. The difference between them on these parts is that Elveden presents a small proportion of two combined removal series on butts, and always a small proportion of final retouch. On the other hand, Hitchin differs from Swanscombe and Elveden on component 1 (**Figure 4**), due to the high intra-site variety of technological features, supporting recent contentions that two separate pulses of occupation are contained in this assemblage (White et al., 2019; Shipton and White 2020), one similar to Elveden and the other to Swanscombe. To see more details on technological features, see SOM **Tables 2–5**.

Despite technological differences between all the sites, a Kruskal–Wallis test for variation in medians across all components (**Figure 4**) indicates that there is no significant inter-site heterogeneity: Component 1 *vs*. Component 2, p = 0.8728; Component 1 *vs*. Component 3, p = 0.8728. Although the technology varies, these assemblages are representing the same technology with a different combination of features, dependent on the knapping aims.

SDI values show high intra-site variability, with medians in the 1 to 3.5 range (**Figure 7**). Elveden represents the opposite case, with the highest SDI values. In general terms, there is a clear relation between number of scars and volume of tools (cm^3), except in the case of Boxgrove (**Table 5**), which presents the lowest values. At this site there is a particular circumstance, where there is a frequent fracturing of blanks during the knapping process, due to internal fissures and geodes. This leads to the loss of the relationship between the metric characteristics of the original blank and the metrical features of the final tool. During this breakage process there is a loss of a part of the initial scar information (SOM **Figure 1**), which is reflected in the relation between the SDI value and the tool's volume (García-Medrano et al., 2019).

DISCUSSION

Long Term Trends and Regionalization of Technology

The significance of variation in handaxe shape has long been a focus of discussion in Britain, where cyclical, climatically-forced fluctuations in ecology, geography and habitability have been argued to provide a discontinuous but understandable pattern of arrival, settlement and abandonment (Preece, 1995; White and Schreve, 2001; Hijma et al., 2012; Ashton et al., 2016; Hosfield and Cole, 2018; Ashton and Davis, 2021; Ashton and Davis, 2021).

The present analysis of six British Acheulean sites from MIS 15 to MIS 11c allows technological and morphological intra and inter-site variation to be explored further. Our results indicate that there are statistically significant morphological groups (**Figure 8**) that accord with previous studies (Roe, 1968; Bridgland and White, 2014, 2015; White, 2015; Ashton, 2016; White et al., 2018, 2019; Davis and Ashton 2019; Shipton and White, 2020; Davis et al., 2021a; Ashton and Davis 2021). The analysis shows that most of the tools occupy overlapping shape space for the first two principal components. Nevertheless, these groups are statistically distinguishable. There is a clear distance from the highest morphometrical variability at Brandon Fields to MIS 13 sites, which reflect the most ovate and standardized assemblages. MIS 11c sites appear to reflect two main shape groups: Elveden, which has a tendency to oval shapes, similar to those from MIS 13; and the more pointed planforms at Swanscombe and Hitchin.

The characteristic handaxes from Brandon Fields of thick, elongated forms with irregular edges, have parallels with several other early sites in eastern and southern England. Maidscross Hill, 4 km south-west of Brandon Fields, also lies on the Timworth Terrace of the Bytham River with the majority of handaxes being abraded and of a similar form to those from Brandon Fields, probably dating to MIS 15 (Flower, 1869; Davis

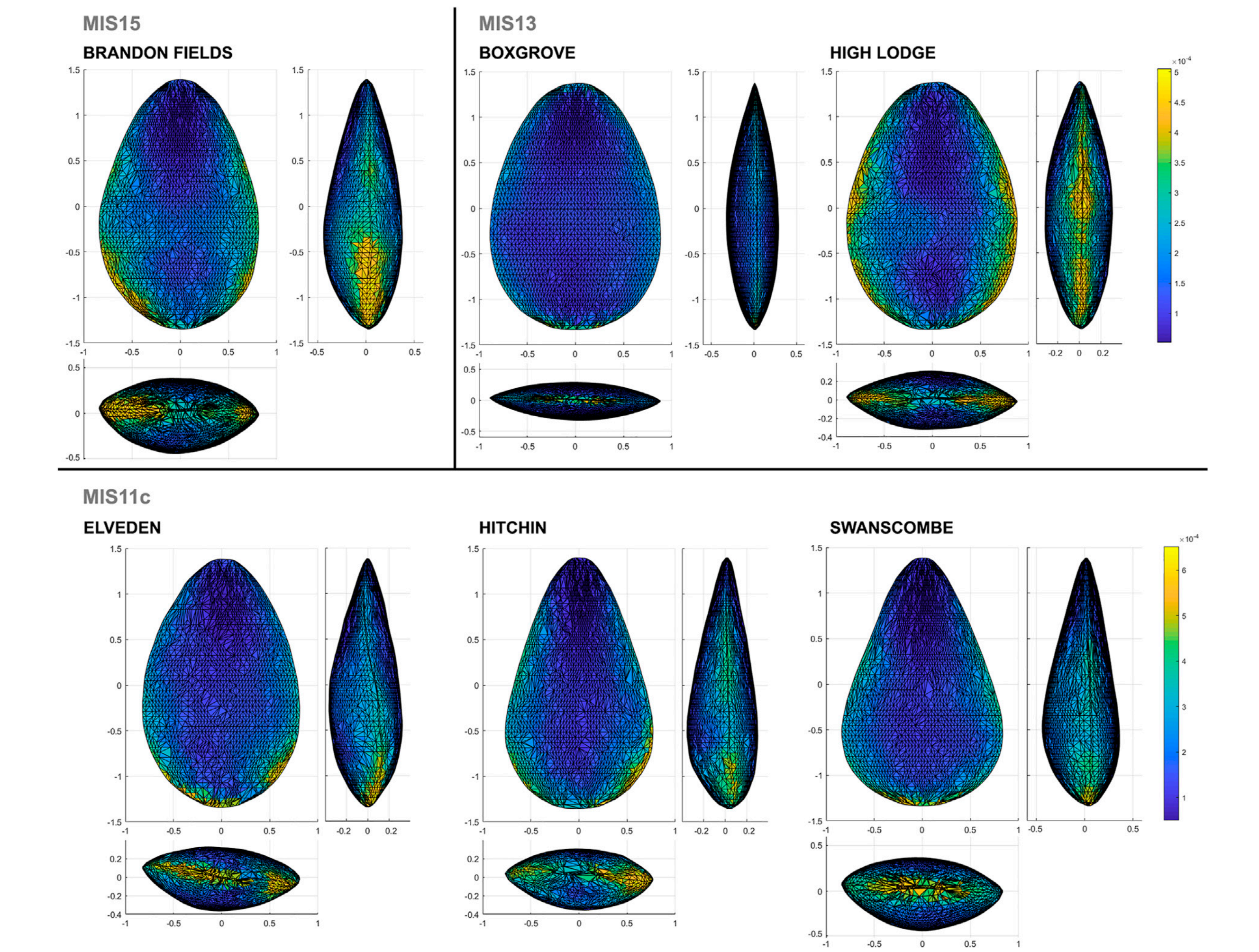

FIGURE 3 | The mean shapes of handaxes and cleavers. Color coding represents the relative degree of variability of each individual landmark reflecting the spatial distribution of variability across the tools.

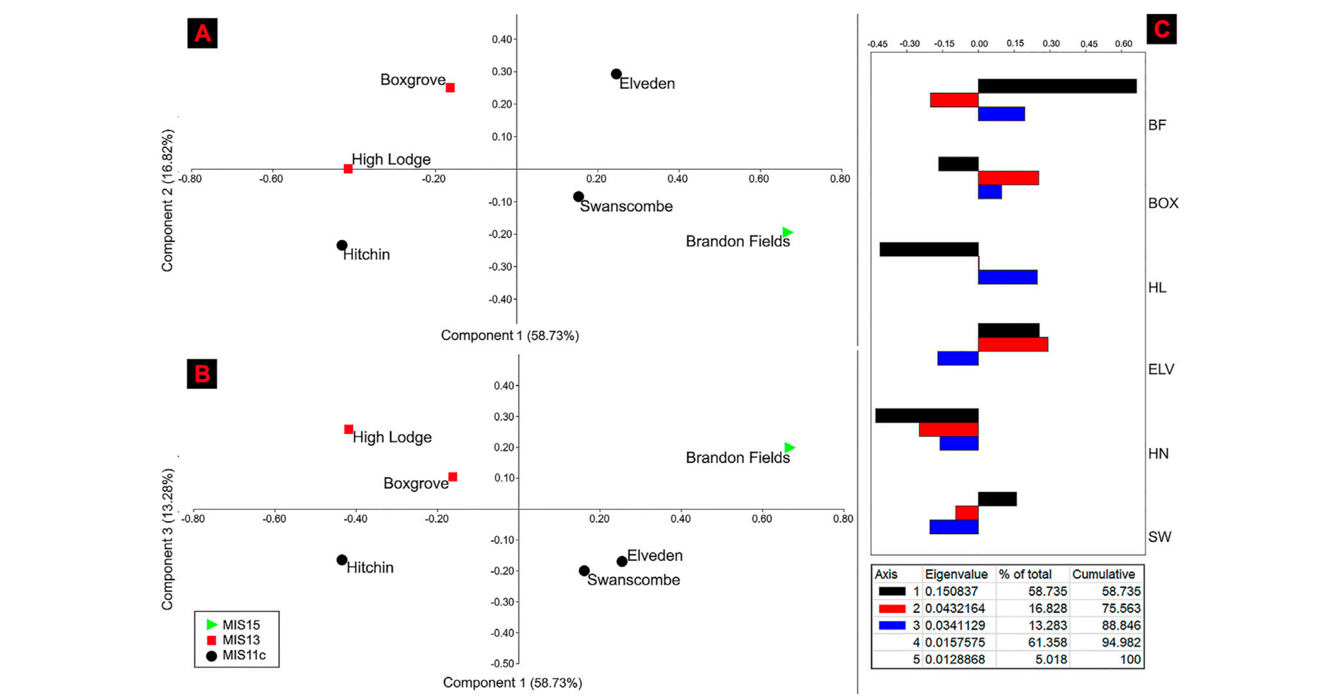

FIGURE 4 | Correspondence Analysis (CA) resulting from combining all the technological features by sites (SOM **Tables 1–4**). **(A)** Component 1 and 2; **(B)** Components 1 and 3; **(C)** Components loadings per site. Abbreviations: BF, Brandon Fields; BOX, Boxgrove; HL, High Lodge; ELV, Elveden; HN; Hitchin, SW, Swanscombe.

et al., 2021a; Lewis et al., 2021). The complex sediments at Warren Hill a further 8 km to the south of Maidscross Hill, reflect the final iteration of the Bytham River, dating to MIS 12. It has three intermixed, derived assemblages, the most abraded of which is characterised by handaxes similar to those from Brandon Fields and Maidscross Hill (Roe, 1968; Wymer, 1985; Davis et al., 2021a; Lewis et al., 2021). This part of the assemblage is also argued to date to MIS 15. Beyond the Bytham system, Fordwich (Kent) is on a high terrace of the River Stour and has long been suggested to have an early date (Bridgland et al., 1998; Bridgland and White, 2014; White, 2015). Current fieldwork is investigating the context of the artefacts alongside a new dating programme with initial results supporting a pre-Anglian age (Key, in review). Although there is variation in handaxe form, many are elongated, thick ovate shapes with evidence of occasional soft hammer use. Roe (1968) placed the assemblage in his Group V, alongside the "worn series" from Warren Hill. Finally, Farnham on the River Wey in Surrey has artefacts from several terraces, with a small assemblage of handaxes from the highest and oldest Terrace A (Oakley, 1939; Roe, 1968). They were also placed by Roe in his Group V, united by "the coarse character of the handaxe industries belonging to it" (Roe, 1968, 65). Although precise dating is lacking for some sites, there does appear to be a group of handaxe assemblages that adhere to the form of those from Brandon Fields, probably dating to MIS 15.

From MIS 15 to 13, there is a transition towards a consistent technological approach with the maximum development of shaping strategies through several removal series plus final retouch on the whole perimeter of the tool, as represented by the late MIS 13 sites of Boxgrove and High Lodge. The high degree of invasiveness of this technology has a clear effect on the refinement of handaxes, which increase by 28% (SOM **Table 1**). These sites show the consistency of the technology from a technological and morphometrical point of view, with high standardization values and a correspondence between technology and morphometry. They tend towards refined ovate forms with soft hammer flaking, marginal trimming of the middle and butt portions, and are also characterised by frequent use of tranchet sharpening. Similar handaxes have been noted from Corfe Mullen (Roe, 2001; McNabb et al., 2012; Davis, 2013) and Ridge Gravel Pit (Davis, 2013; Davis et al., 2021b) in the Solent Basin, where the terrace gravels have been tentatively attributed to MIS 13. The Boxgrove assemblage was excavated after Roe's (1968) analysis, but Corfe Mullen and High Lodge were both placed in his Group VII.

From MIS 11c, the technology behind the morphological groups (oval vs. pointed) does not reflect the particularities used to define each site by itself. There is variation in the combination of the same technological features, adapted to the final shaping aim. Technology reveals less standardization, with the major heterogeneity documented on tips, but without any statistically significant difference. The technology acquired a new sense of plasticity, becoming flexible and adapted to the features of the blank and towards achieving the final template. Thus, the only difference between sites is the

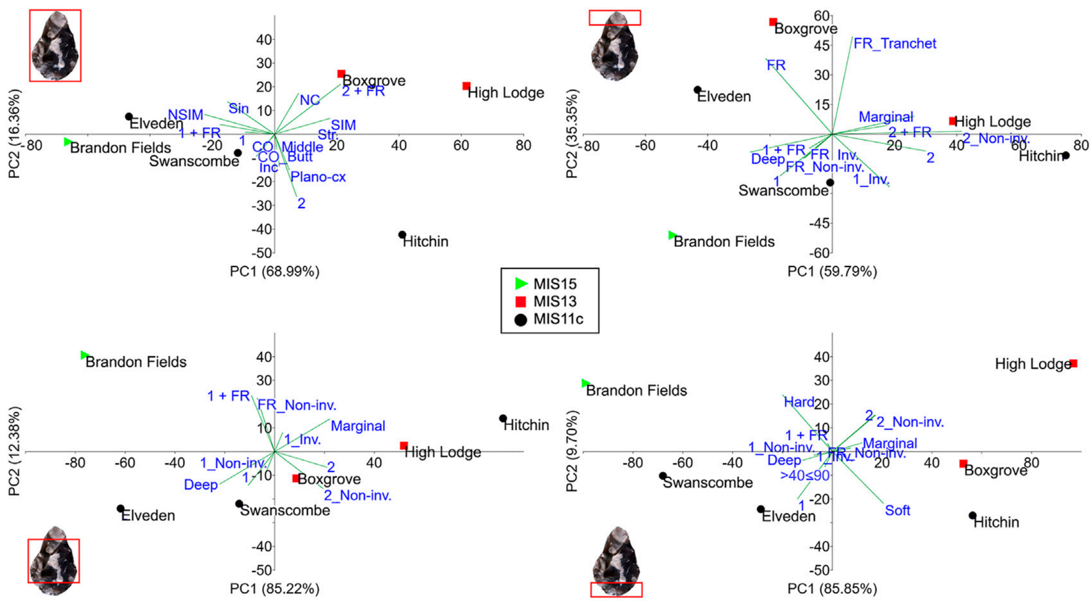

FIGURE 5 | PCA (biplots) of the technological features, which have a major effect on each group. The four graphs correspond with the technological variables included in **Figure 4** but divided in: **(A)** General aspects; **(B)** Distal part; **(C)** Mid-part; **(D)** Proximal part. In blue, technological features which contribute to the distribution of sites. Abbreviations: Hard, hard percussion; Soft, soft percussion; H/S, combined; 1, one removal series; 2, two removal series; 1+FR, one plus Final Retouch; 2+FR, two plus Final Retouch; CO_Butt, cortex in butts; CO_Butt + Mid, cortex in butts and mid-parts; CO_All, cortex in the whole instrument; CO_Midddle, Cortex in the mid-parts; NC, no cortex; Str, straight edges; Sin, sinuous edges; Inc, incurved edges; SIM, symmetric profile; NSIM, non-symmetric profile; Pl-cx, Plano-convex profile; Deep, deep effect on edges; Marginal, marginal effect on edges; 1_Inv., first invasive removal series; 1_Non-inv., first non-invasive removal series; 2_Inv., second invasive removal series; 2_Non-inv., second non-invasive removal series; FR. Inv., invasive Final Retouch; FR. Non-inv., non-invasive Final Retouch; FR_Tranchet, Distal tranchet Final Retouch).

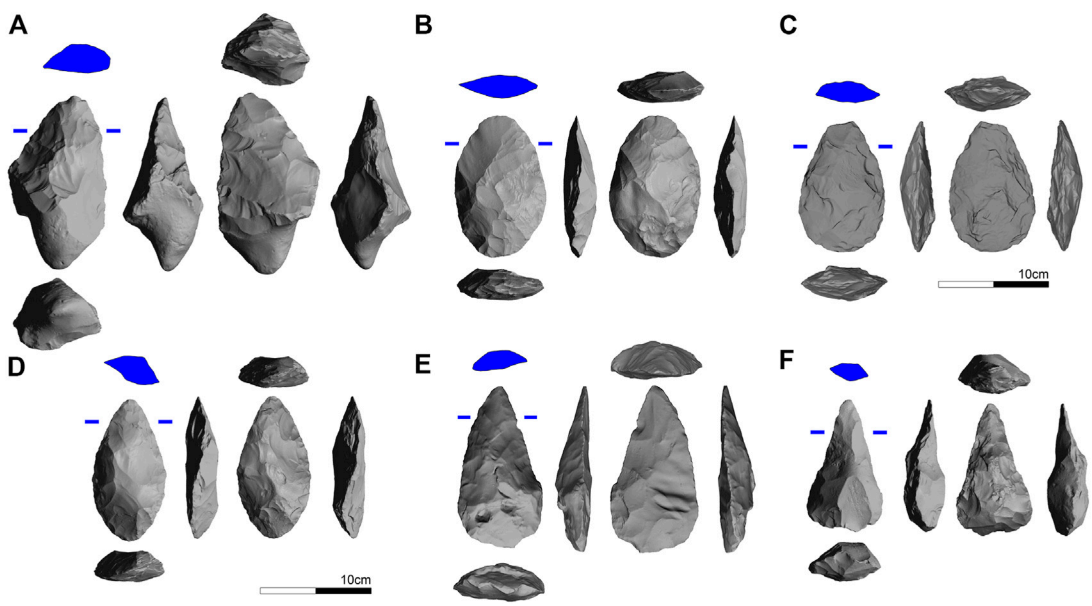

FIGURE 6 | Handaxe examples from each site: **(A)**, Brandon Fields (Sturge_14); **(B)**, Boxgrove (Q1B_Unit4_95_L1097); **(C)**, High Lodge (3,177); **(D)**, Elveden (Sturge_92); **(E)**, Hitchin (272); **(F)** Swanscombe (16). In blue, transversal sections at upper fifth.

TABLE 4 | Summary statistics for deviations from perfect bilateral and bifacial symmetry and edge irregularity.

		Deviation from bilateral symmetry	Deviation from bifacial symmetry	Left edge planform irregularity	Right edge planform irregularity	Right section irregularity
BF *n* = 49	Min	1,85	1,56	36,70	37,20	24,88
	Max	15,93	15,01	180,23	169,57	341,70
	Mean	5,49	4,88	85,18	79,73	106,00
	Std. error	0,42	0,39	4,90	4,41	9,55
	SD	2,95	2,71	34,32	30,86	66,88
	CV	53,78	55,43	40,29	38,70	63,09
BOX *n* = 86	Min	0,99	1,22	26,72	20,13	16,51
	Max	9,29	7,28	152,34	163,54	105,91
	Mean	3,63	3,07	74,84	73,87	51,45
	Std. error	0,16	0,14	3,18	3,26	1,99
	SD	1,47	1,32	29,46	30,26	18,43
	CV	40,51	43,02	39,37	40,96	35,82
HL *n* = 32	Min	1,85	1,54	32,71	27,65	26,70
	Max	6,71	8,67	168,06	145,07	106,52
	Mean	3,13	2,89	64,07	67,07	51,84
	Std. error	0,23	0,24	5,67	4,47	3,64
	SD	1,31	1,34	32,07	25,27	20,60
	CV	41,95	46,23	50,06	37,68	39,73
ELV *n* = 29	Min	2,30	2,06	12,02	25,58	20,95
	Max	13,74	10,12	131,22	167,26	183,76
	Mean	5,71	4,39	66,29	72,39	84,50
	Std. error	0,45	0,34	5,04	6,27	7,55
	SD	2,41	1,83	27,13	33,77	40,68
	CV	42,16	41,79	40,93	46,64	48,14
HN *n* = 29	Min	2,09	1,77	38,66	32,23	27,16
	Max	16,15	16,19	221,94	244,22	191,64
	Mean	5,69	5,27	105,16	110,93	78,48
	Std. error	0,56	0,62	8,68	11,88	7,74
	SD	3,00	3,34	46,74	63,98	41,68
	CV	52,73	63,35	44,45	57,68	53,11
SW *n* = 85<	Min	2,16	1,66	26,73	30,57	23,00
	Max	18,80	12,80	316,95	242,32	271,70
	Mean	6,33	4,84	118,92	109,82	85,16
	Std. error	0,38	0,27	5,98	4,76	5,20
	SD	3,49	2,48	55,16	43,87	47,94
	CV	55,20	51,20	46,38	39,95	56,30

Abbreviations: BF, Brandon Fields; BOX, Boxgrove; HL, High Lodge; ELV, Elveden; HN; Hitchin, SW, Swanscombe.

TABLE 5 | MANOVA results between SDI and volume (cm^3) of tools per site.

	F	df	p	r2
BF	39.08	48	˂0.001	0.450
BOX	8.79	85	0.003	0.0948
HL	38.47	31	˂0.01	0.5619
ELV	11.89	25	0.002	0.3313
SW	67.6	82	˂0.001	0.545
HN	71.31	28	˂0.001	0.725

Abbreviations: BF, Brandon Fields; BOX, Boxgrove; HL, High Lodge; ELV, Elveden; HN; Hitchin, SW, Swanscombe.

relative abundance of particular features over others. For example, we can associate the more oval, refined and twisted-profile shapes of Elveden with a longer shaping sequence around the whole perimeter of tools, with very invasive removal series, including butts, and a frequent use of tranchet blows on tips. By contrast, for Swanscombe these sequences were adapted, keeping a significant part of the original cortex on butt and mid-parts, and with tips shaped by the combination of a first invasive removal series, a second non-invasive one, and then final retouch. The knappers' emphasis on the distal ends, reduced the tip width, creating a shift of the maximum width to the mid to butt parts of tools. Hitchin is more difficult to interpret, due to its high variability.

Exploring the relation between width and thickness at the tip (at 1/5 Length) and butt (at 4/5 Length), we can detect that tip thickness is similar between sites and without any chronological pattern. Nevertheless, the flaking on tips produces a progressive chronological decrease of tip width (**Figure 9**). Tips are wider in oval samples, and narrow in pointed tools. In this case, butts reflect greater variability than

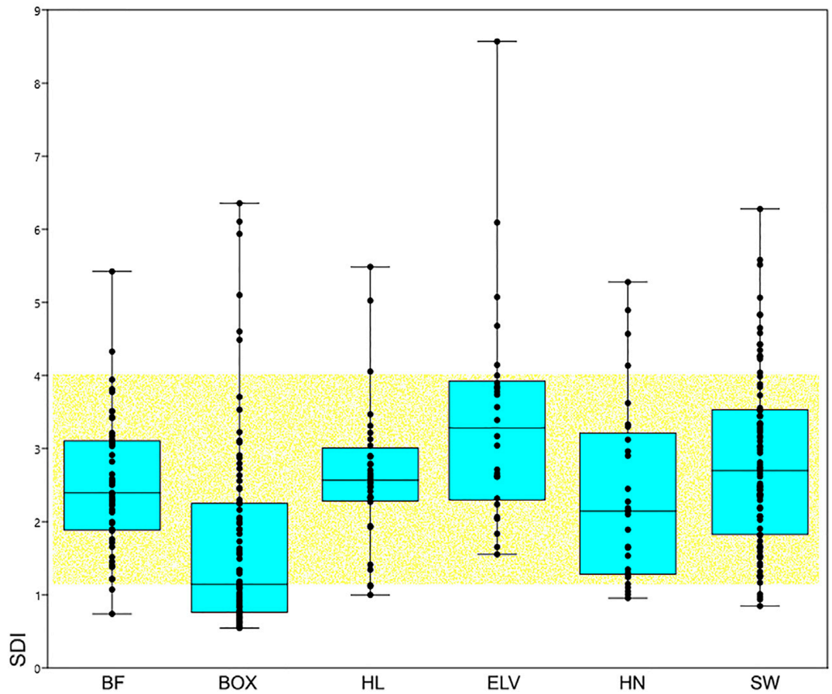

FIGURE 7 | Boxplot with jitter of SDI (scars per in^2) distribution per sites. Abbreviations: BF, Brandon Fields; BOX, Boxgrove; HL, High Lodge; ELV, Elveden; HN; Hitchin, SW, Swanscombe.

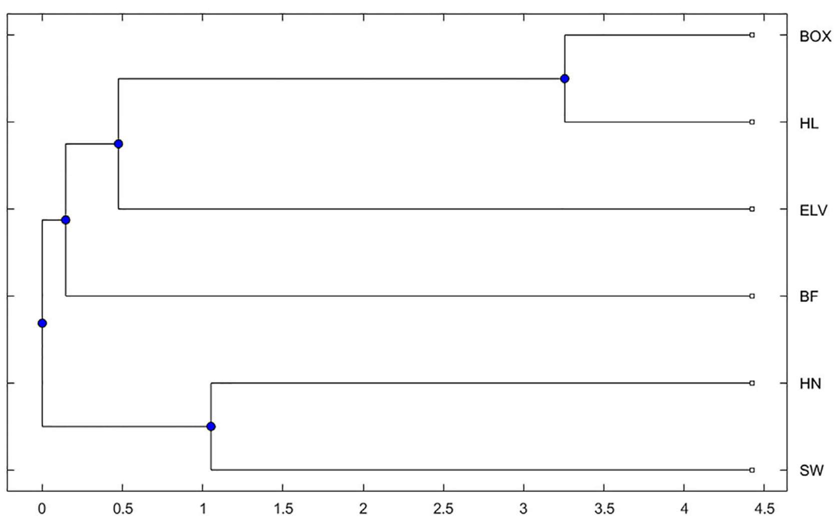

FIGURE 8 | Cluster and distances of sites from the Geometric Morphometrics analysis. Abbreviations: BF, Brandon Fields; BOX, Boxgrove; HL, High Lodge; ELV, Elveden; HN; Hitchin, SW, Swanscombe.

tips, without any clear pattern. The only aspect to highlight is the small butt width of Elveden tools.

The ovate to cordiform-shaped handaxes from Elveden, often with twisted profiles, have possible parallels with other contemporary sites in East Anglia. The small assemblage from Barnham (7 km to the east) contains several twisted ovates (Davis and Ashton, 2019), while ovates also predominate in the small assemblage from Beeches Pit (10 km to the south; Gowlett et al., 2005). A further site is Foxhall Road in Ipswich (50 km south-east of Elveden), where twisted ovates were recovered from lacustrine clays in the excavations by Nina Layard (1904, 1906). Recent reassessment has interpreted the clays as Hoxnian lake beds

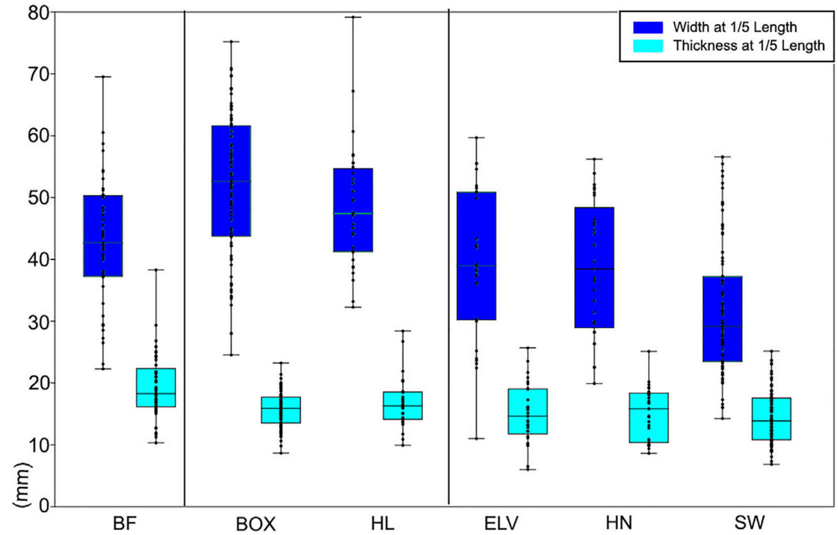

FIGURE 9 | Boxplot with jitter of Tip width and thickness. Abbreviations: BF, Brandon Fields; BOX, Boxgrove; HL, High Lodge; ELV, Elveden; HN; Hitchin, SW, Swanscombe.

(White and Plunkett, 2004) with unpublished OSL dates of 416 ± 36 ka and 434 ± 54 ka (see White et al., 2019).

The handaxes from the Middle Gravels at Swanscombe are typically small, pointed forms with thick butts that sometimes retain cortex. There are other sites on the same Orsett Heath/ Boyn Hill Thames terrace as Swanscombe, which can be broadly attributed to MIS 11. Chadwell St Mary is 7 km downstream, where at least 126 handaxes were recovered from a series of gravel pits and have similar pointed forms to those from Swanscombe (Roe, 1968; Wymer, 1985). Both sites were placed in Roe, (1968). The East Burnham sites of Cooper's and Deverill's Pits are 60 km upstream (Lacaille, 1939; Wymer 1968) and of 300 recorded handaxes, most are again pointed in form.

Unlike earlier periods, there do appear to be regional patterns in MIS 11. Palynology and molluscan biostratigraphy suggest that the assemblage from Swanscombe is contemporary to those from Elveden, Barnham, and Beeches Pit, all attributed to the transition between Hoxnian pollen zones II and III with the resolution of the dating perhaps as little as 2,000 to 3,000 years (Ashton, 2016).

Occupation at Hitchin seems occur in the early interglacial aqueous sediments (Ho II), as well as the overlying colluvial "brickearth" (post-Hoxnian sensu stricto?), and the admixture of these two has probably caused the Hitchin assemblage to be mis-classified. Unfortunately, it has not proved possible to distinguish the two series on the basis of condition, and in the absence of documentary record, only new field investigations will be able to resolve this.

The broader implications of these results are explored below.

Implications for Population Dynamics and Cultural Transmission in Middle Pleistocene Europe

From our study we can surmise that technology reflects an underlying continuum of knowledge accumulation, with small technical variations contributing to the morphological groups identified. The results suggest that there are long-term technological trends from MIS 15 through to MIS 13. These include the broad maintenance of the bifacial concept with the increase in soft-hammer flaking that enabled the production of thinner tools with more regular, functional edges. The relatively simple handaxe forms of MIS 15 saw a trajectory of gradual functional improvement in MIS 13 through better and more extensive cutting edges with sharpening or resharpening by tranchet blows to the tip. This specific practice may also reflect greater curation of handaxes during MIS 13 (Emery, 2010). If Britain was depopulated during MIS 14, then the results suggest that the returning populations in MIS 13 come from source areas within western or southern Europe (e.g. Antoine et al., 2016), without any clear indication of innovation from further afield.

The maintenance of technology and form in late MIS 13 could suggest strong cultural links across areas of up to 300 km. Alternatively it could reflect rapid colonisation by related groups with the conservative maintenance of more isolated practice through strong social norms. A further option is that colonisation of these areas was of short duration with insufficient time for diversification from established practice. Whatever the answer, it is probable that normative behaviour, governing the form handaxes should take and the techniques used to make and re-sharpen them, was established by MIS 13 (Shipton and White, 2020).

By MIS 11 there is a pattern of regionalisation in material culture, with distinctions in handaxe forms between the Thames Valley and central East Anglia. It has previously been suggested that these regions could reflect related group territories with potential radii of c. 30–40 km (Davis and Ashton, 2019; Shipton and White, 2020; Ashton and Davis, 2021). This order of territory size in temperate environments has been argued to be sufficient to support groups of c. 150 people, dependent on the technological ability to convert usable biomass into food (Ashton and Davis, 2021). A similar size for groups, or related sub-groups, is also suggested to be biologically viable as a breeding population (Wobst, 1974), and furthermore corresponds with the number of maintainable relationships in the Social Brain Hypothesis (Dunbar, 1998, 2003).

If the East Anglian and Thames Valley MIS 11 sites do represent different territories, then their contemporaneity and marked distinction in material culture would suggest different populations entering Britain, rather than *in situ* divergence. The East Anglian sites could relate to populations arriving via the East Anglian rivers, such as the Suffolk Stour, or the Waveney, while Swanscombe, Chadwell St Mary and East Burnham are all linked by the River Thames. Hitchin could conceivably have multiple periods of occupation, and lying midway between the two regions could have archaeological signatures from both. The duration of the East Anglian sites is hard to gauge, but an important contribution of Swanscombe is the persistent manufacture of the same forms of handaxes throughout the 2 m depth of the Middle Gravels, indicating a stable population for several thousand years.

The regionalisation of material culture by MIS 11 has important implications for the interpretation of lithic assemblages beyond Britain. Ashton and Davis (2021) suggested the Cultural Mosaic Model, whereby in stable environments different cultural expressions developed in part as a reflection of local resources and needs. Changes in environment would trigger shifts in population with an increase in exchange of technological knowledge, acculturation and increased gene-flow. This enabled the transmission of technological practice on a broader scale, such as western and central Europe, where by MIS 11 there is evidence for efficient hunting, skilled butchery, wood-, hide- and bone-working, and the use of fire at several sites across the region (Warren, 1911; Thieme, 1997 the use of fire; Roberts and Parfitt, 1999; Gowlett et al., 2005; Voormolen, 2008; Roebroeks and Villa, 2011; Schoch et al., 2015; van Kolfschoten et al., 2015; Ravon et al., 2016a, 2016b, 2022; Zutovski and Barkai, 2016; Milks et al., 2019).

CONCLUSION

The results of this paper have provided answers to the questions set out in the introduction. The WEAP method as applied to the six sites supports previous work on the identification of chronologically and morphologically distinct groups of sites. Besides, the combination of technological and morphometry give us information at different scales. On the one hand, technology shows a continuum accumulation of knowledge, without abrupt changes. There is a clear transition from a standardization of technology until MIS 13 and then, a plasticity on how this technology is applied at each site, depending in part on raw material quality as well as the final mental template. On the other hand, morphometry reflects the higher degree of regionalization, especially from MIS 11.

Furthermore, there are technological developments that can be identified from MIS 15 sites to those of later periods. The developments are underpinned by increased use of soft hammer flaking, which enabled the production of thinner handaxes with more effective and even cutting edges and the deployment of specific forms of sharpening, such as tranchet finishing. The use of soft hammer also enabled the imposition of greater variety in form and the application of idiosyncratic techniques, such as twisted profiles. Variation in form is first fully expressed in MIS 11, where regional patterns can be identified, unlike earlier periods. These appear to be the expression of small-scale group identity over multi-generational timescales of several thousand years, indicating strong systems of social learning and an adherence to group norms. Normative behavior, as expressed in this case through handaxes, created stronger social bonds and better group cohesion (Shipton et al., 2021) which were arguably essential ingredients for survival of more dispersed populations in northern environments.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

PG-M analyzed all lithic material, organized and analyzed database, analyzed the PG-M results and wrote the manuscript. PG-M and CS made all 3D models used to the PG-M analysis. CS and MW participated in data analysis, statistics and manuscript writing. MW and NA participated in manuscript writing. All authors contributed to manuscript revision, read, and approved the submitted version.

FUNDING

The contribution of PG-M is supported by a Beatriu de Pinós MSCA-COFUND (AGAUR). Besides, she also received a grant from the European Union's Horizon 2020 research and innovation programme as part of a Marie Sklodowska-Curie project, "Western European Acheulean project, WEAP" (Grant No. 748316). The University of Bradford and Adrian Evans, through the "Fragmented Heritage AHRC Project", lent us the scanner for part of the work. The latter has received financial support from the Spanish Ministry of Science and Innovation through the "María de Maeztu" program for Units of Excellence (Grant No. CEX 2019-000945-M). Research carried out at IPHES is in the context of projects Grant No. PGC 2018-093925-B-C32 (MICIN), 2017SGR-1040 (AGAUR), and 2019PFR-URV-91 (URV). The contribution of NA was supported by the Pathways to Ancient Britain Project funded by the Calleva Foundation.

ACKNOWLEDGMENTS

We are particularly grateful to the Hebrew University of Jerusalem, Leore Grosman and Antoine Muller, who helped us with the AGMT3-D software management. The analysis has been done between the Department Britain, Europe and Prehistory at Franks House (British Museum), and the Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA, Spain). We also thank editors and reviewers for all the revision and suggestions, which has highly contributed to improve the quality of this work.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2022.917207/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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ORIGINAL RESEARCH
published: 20 June 2022
doi: 10.3389/feart.2022.893473

The Sedimentary Context of El Kherba Early Pleistocene Oldowan Site, Algeria: Sediment and Soil Micromorphology Studies

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A comprehensive investigation is conducted on the archeological sediments from the Early Pleistocene site of El Kherba (Algeria), involving sediment and soil micromorphology analyses. El Kherba yielded Oldowan stone tools associated with animal fossils from three archeological levels. The studies aim at assessing the sedimentary processes that acted in the burial of the archeological remains and at identifying microfacies in order to gain high-resolution paleoenvironmental information pertaining to early hominin behavioral activities at the site 1.8 million years ago. The data indicate that the archeological assemblages accumulated in sediments with fine-grained particles, primarily silt and clay of massive structure, in a floodplain landscape in a temperate climate in the lower part of the stratigraphy and a gradual change from humid to arid environment in the upper part. These results are also supported by taphonomic and isotope studies carried out previously on the site.

Keywords: grain size, micromorphology, El Kherba, Oldowan, Early Pleistocene, Algeria, Lower Paleolithic

OPEN ACCESS

Edited by:
Marie-Hélène Moncel, Director of Research CNRS-MNHN, France

Reviewed by:
Michael Chazan, University of Toronto, Canada
Mathieu Rué, Paléotime, France

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Specialty section:
This article was submitted to Quaternary Science, Geomorphology and Paleoenvironment, a section of the journal Frontiers in Earth Science

Received: *10 March 2022*
Accepted: *29 April 2022*
Published: *20 June 2022*

Citation:
Abdessadok S, Sahnouni M, Harichane Z, Mazouni N, Chelli Cheheb R, Mouhoubi Y, Chibane S and Pérez-González A (2022) The Sedimentary Context of El Kherba Early Pleistocene Oldowan Site, Algeria: Sediment and Soil Micromorphology Studies. Front. Earth Sci. 10:893473. doi: 10.3389/feart.2022.893473

1 INTRODUCTION

Appraising site formation processes is nowadays an essential component in Paleolithic studies. It seeks to decipher the nature of the agencies, geological or behavioral, which were primarily involved in the accumulation of fossil bones and stone artifacts in early Paleolithic sites. This enquiry is commonly approached by 1) assessing the taphonomic grade of fossil bones (e.g., Shipman, 1981; Lyman, 1994) and 2) identifying agents responsible for stone artifact concentrations (e.g., Schick, 1986). While bone taphonomic conditions and artifact concentration patterns are important criteria, the sediments encasing the archeological remains are equally crucial for reconstructing site formation processes (e.g., Hassan, 1978). They represent a line of evidence of major interest for contextualizing Paleolithic archeological assemblages. Moreover, the sediments are considered "artifacts" as they are tightly part of the archeological record along with other behavioral objects (Goldberg and Berna, 2010). They provide valuable information not only on the depositional dynamics by which artifacts were incorporated into the sedimentary matrix but also on the paleoenvironmental conditions prevailing during early hominin behavioral activities.

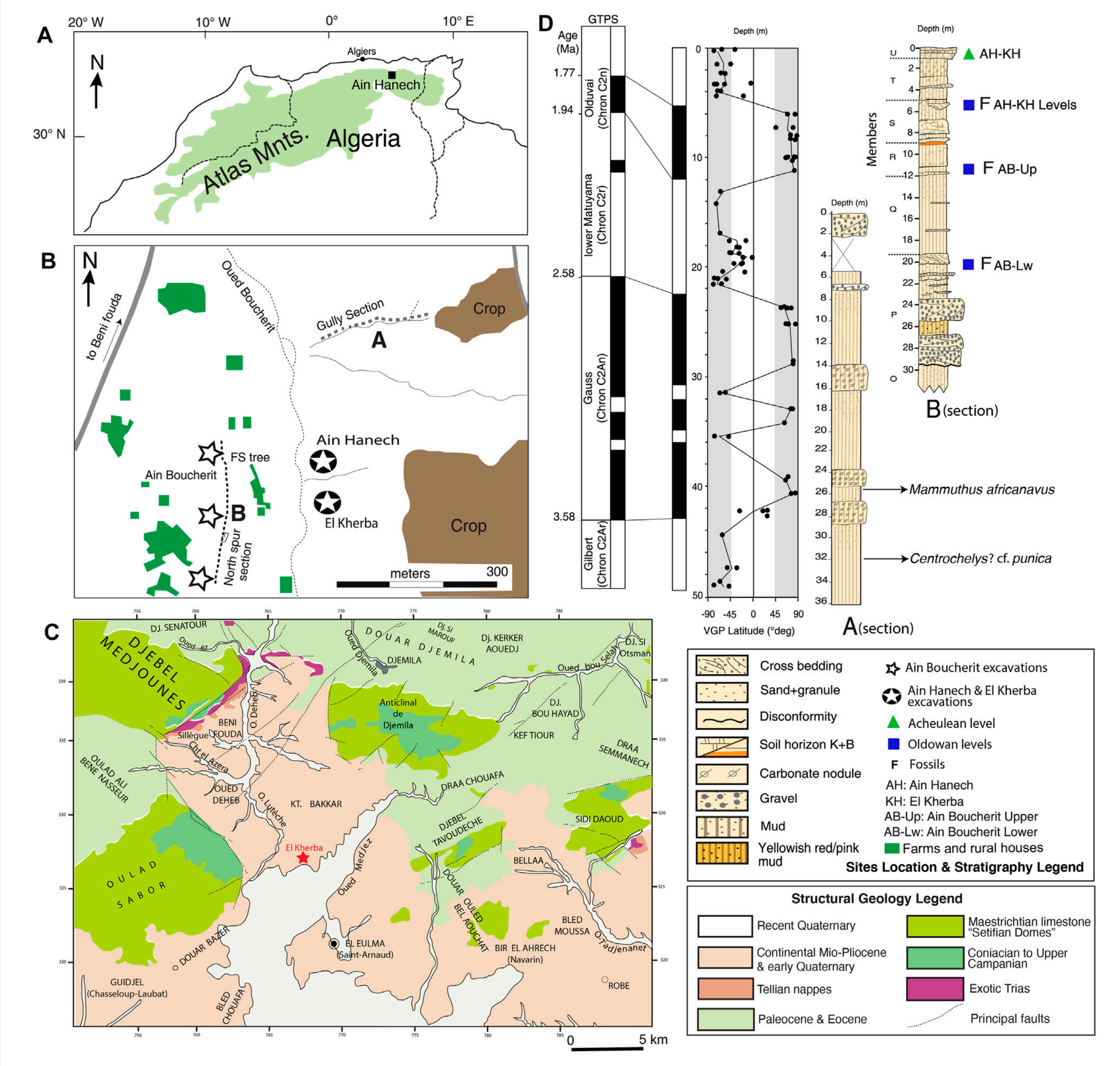

FIGURE 1 | Geography and geology of El Kherba, including **(A)** geographic situation of the Ain Hanech research area within Algeria, **(B)** situation of the El Kherba Oldowan site within the Ain Hanech research area, **(C)** El Kherba regional geological context (redrawn after El Eulma geological map, 1/50 000, 1977), and **(D)** stratigraphic and magnetostratigraphic position of El Kherba deposit within the Ain Hanech formation (modified after Sahnouni, 1998).

Comprehensive examination, usually employed in Paleolithic archeology to assess the sedimentary context of archeological assemblages, comprises chiefly three lines of evidence: stratigraphic description, grain size characteristics, and soil micromorphology. The stratigraphic evidence provides a gross depiction of the sedimentary context of the archeological remains, e.g., fine-grained versus coarse-grained sediments. The size of sedimentary particles is indicative of flow velocity (Hassan, 1978). For instance, fine-grained sediments settle from suspension at a lower velocity regime, such as particles deposited in lakes and flood basins. On the contrary, coarser grains such as sands and gravels are deposited at river channels with a high velocity regime. Soil micromorphology provides high-resolution data that "can discriminate the sedimentary signatures diagnostic of human-related activities from natural phenomena" (Courty, 1992). Furthermore, it offers detailed paleoenvironmental information that can help reconstruct early hominin behaviors and their use of the landscapes (Mallol, 2006; Mallol et al., 2011).

This paper presents detailed sedimentological and micromorphological studies of the fluvial sediments containing the Oldowan assemblages of the Early Pleistocene site of El Kherba in northern Algeria. The studies aim at appraising the processes that acted in the accumulation of the archeological remains at the site and at identifying microfacies in order to acquire high-resolution paleoenvironmental data that took place at El Kherba 1.8 million years ago (Ma). After conducting analyses on stone artifact concentrations (Sahnouni and de Heinzelin, 1998) and on the taphonomic grades of fossil bones (Sahnouni et al., 2013), the sediment studies aided in obtaining a complete picture of the sedimentary context enclosing the Oldowan occurrences excavated in this key Early Pleistocene site in North Africa. In addition, the results of the sediment and micromorphological studies are corroborated with data emanating from taphonomic and paleoecological investigations previously undertaken at the site. The implications on reconstructing Oldowan hominin behavioral patterns are also highlighted.

2 SITE BACKGROUND, STRATIGRAPHY, AND DATING

2.1 Site Background

El Kherba is situated in the Ain Hanech area on the edge of the eastern Algerian High Plateaus in the Sétif Province (**Figure 1A**) 7 km northwest of the city of El Eulma at the southern limit of the Neogene Beni Fouda sub-basin in a sedimentary outcrop cut by the deep ravine of the intermittent Oued Boucherit (895 m a.s.l.). The archeological site is located at 960–970 m a.s.l. on the northeast–southwest escarpment of Guelta Zerga (100 m higher) created by the fluvial networks of Oued Deheb that flows toward the Mediterranean. Morphostratigraphically, the site represents the end of the filling of the tertiary continental Beni Fouda sub-basin by fluvial channels carrying sediments from the margins of the Tellean formations made of gravels, sands, and floodplain muds, forming alluvial plains draining to the southwest toward the El Eulma area.

The site was discovered in 1992 following new investigations launched in the Ain Hanech research area (Sahnouni, 1998; Sahnouni and de Heinzelin, 1998). Large-scale excavations have been carried out at El Kherba yielding a rich and diverse Early Pleistocene fauna associated with Oldowan stone tools. The fauna includes Gasteropoda indet., *Mauremys leprosa*, Crocodylia indet., *Canis primaevus*, *Crocuta crocuta*, *Panthera* sp., *Felis*? *Lagomorpha*, *Elephas moghrebiensis*, *Ceratotherium mauritanicum*, *Equus tabeti*, *Equus* aff. *oldowayensis*, *Hippopotamus gorgops*, *Kolpochoerus heseloni*, *Giraffa pomeli*, *Sivatherium maurusium*, *Pelorovis howelli*, *Gazella pomeli*, and *Numidocapra crassicornis* (Sahnouni and Van der Made, 2009: Sahnouni et al., 2018). Overall, the fauna suggests a more or less open and dry landscape. However, the occurrence of a permanent body of water is indicated by the remains of crocodile, aquatic turtle, and hippopotamus. The faunal paleoecological reconstruction is supported by isotopic evidence of pedogenic carbonates indicative of a savanna ecosystem with expanding grassland vegetation and increasing aridification through time at El Kherba (Sahnouni et al., 2011).

The stone tool assemblages are made primarily of limestone and flint. They comprise cores and core-forms, whole flakes, retouched pieces, and fragments (**Figure 2**). The cores and core-forms include unifacial and bifacial choppers, polyhedrons, subspheroids, spheroids, and simple cores. The technological and typological characters show that the assemblages of Oldowan are very similar to those from Olduvai Upper Bed I and Lower Bed II in Tanzania, especially in terms of flaking patterns and resultant artifact forms (Sahnouni, 1998; 2006). Evidence, of usewear traces on several artifacts and of cut-marked and hammerstone-percussed bones, indicates that El Kherba was a place for intense subsistence activities by early hominins (**Figure 2**), including disarticulating and removing meat and breaking bones of large mammals to extract marrow (Sahnouni et al., 2013).

2.2 Regional Stratigraphy and Dating

The Sétif region is part of the Maghrebid chain formed during the alpine orogeny. It is composed mainly of marl lands of Middle Cretaceous to Neogene age (**Figure 1C**) (Djenba, 2015). The El-Eulma area, located 25 km east of Sétif, is a vast depression composed of six sub-basins (Demdoum, 2010), including the Beni Fouda sub-basin that contains the Ain Boucherit–Ain Hanech Plio-Pleistocene deposits (Duval et al., 2021). The deposits of this basin are of variable facies that consist of red clay fluvio-lacustrine sediments overlaid by heterogeneous beds of several tens of meters thick gray–yellow marls containing limestone concretions and interbedded pebbles, gravels, and sands (Demdoum, 2010). This sequence is often covered with a massive calcrete deposit that can reach 3 m of thickness in some places (Djenba, 2015).

The Oldowan site of El Kherba forms part of the Ain Boucherit–Ain Hanech Plio-Pleistocene sequence, which consists of a succession of paleontological and archeological deposits estimated to be between 4 and 1.67 Ma in age (Sahnouni et al., 2018; Duval et al., 2021). Other Oldowan localities nearby include Ain Boucherit Lower (AB-Lw), Ain Boucherit Upper (AB-Up), and Ain Hanech (**Figure 1B**). All the Oldowan deposits are encased in the 29 m thick Ain Hanech formation that comprises six stratigraphic members named, from bottom to top, P, Q, R, S, T, and U (**Figure 1D**) of fluvial origin made of alternating gravels and sandstone with mudstone (Sahnouni and de Heinzelin 1998; Sahnouni et al., 2018). El Kherba deposits were formed in Member T and slightly in the uppermost part of Member S (**Figure 3**). Member T is 4 m thick and is mainly a muddy unit, light brown (7.5 YR 6/4) or pink (7.5 YR 7/4) in color with carbonated nodulations in its final 2 m. Based on magnetostratigraphy, ESR dating, and biochronology of large mammals (proboscideans, equids, and suids), Ain Hanech and El Kherba deposits date to 1.78 Ma (Parés et al., 2014). The AB-Lw and AB-Up Oldowan deposits, situated lower in the stratigraphy, date to 2.44 Ma and 1.92 Ma, respectively (Sahnouni et al., 2018; Duval et al., 2021).

2.3 Site Stratigraphy

El Kherba stratigraphy is studied in three profiles within the excavation set out altimetrically so that the site stratigraphy can

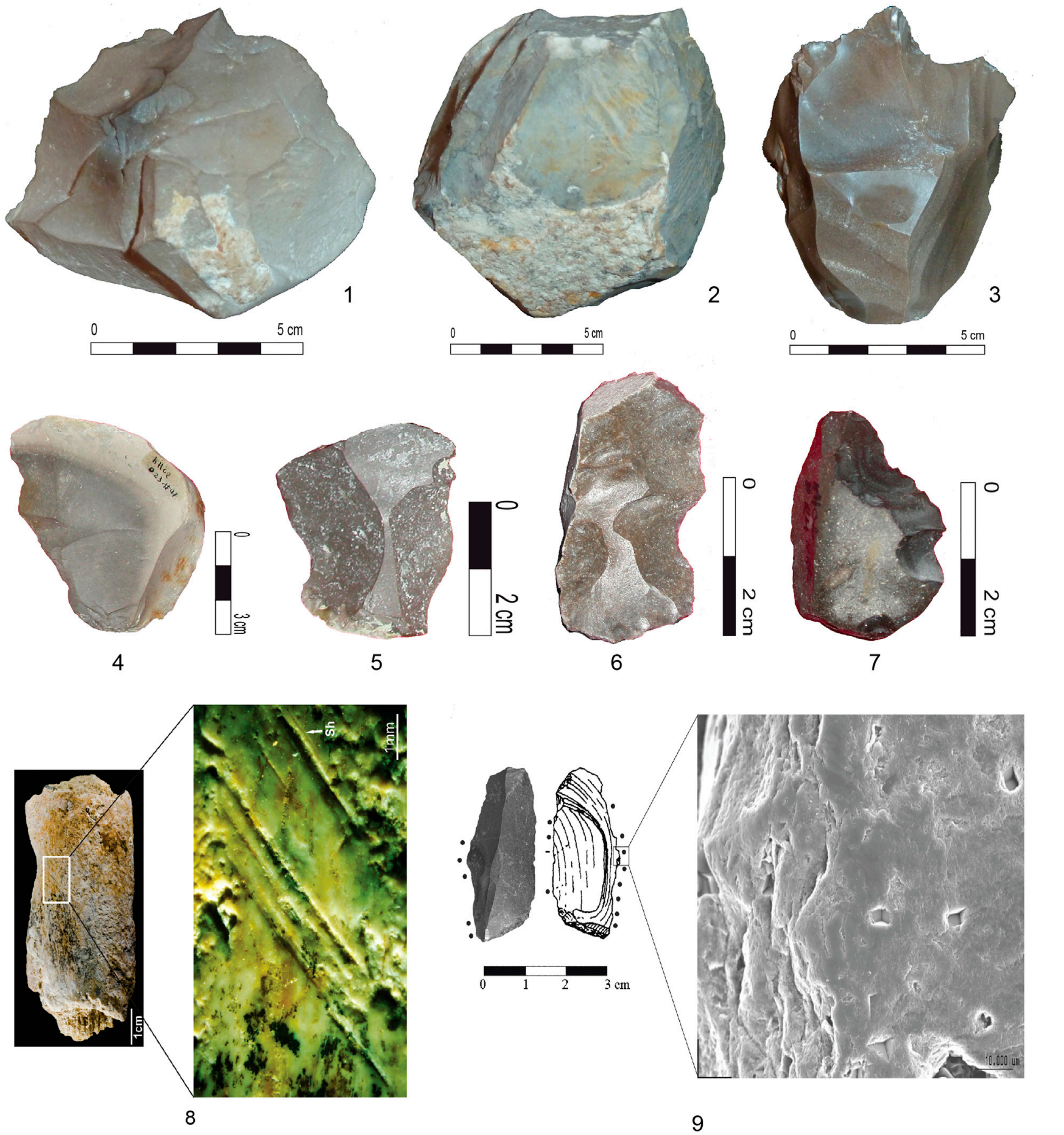

FIGURE 2 | Oldowan stone tools made of limestone and flint and an associated fossil bone from the Early Pleistocene site of El Kherba (Algeria), including (1) a bifacial chopper, (2) a polyhedron/core, (3) a core, (4–6) whole flakes, (7) a denticulate-like retouched piece, (8) a hippopotamus cut-marked rib fragment, and (9) a whole flake with evidence of usewear in cutting meat.

be described in its entirety from top to base. These include deposits in quadrant T29 of Block II (1.90 m thick), in quadrant X32 of Block II (0.90 m thick), and in quadrants N32–N33–N34–N35 (2 m thick) of Block I (**Figure 3**, Supplementary Figure S2). The correlation of these three profiles allowed us to compose a synthetic stratigraphic log of 4.80 m thickness in which 11 layers have been recognized (**Figure 3**) based on sediment texture, consistency, and color. Additional criteria were also considered in discerning the layers including proportion and granulometry of coarse elements and their nature and degree of wear and alteration, paleontological content, and, if necessary, crusting, bioturbations, and metallic

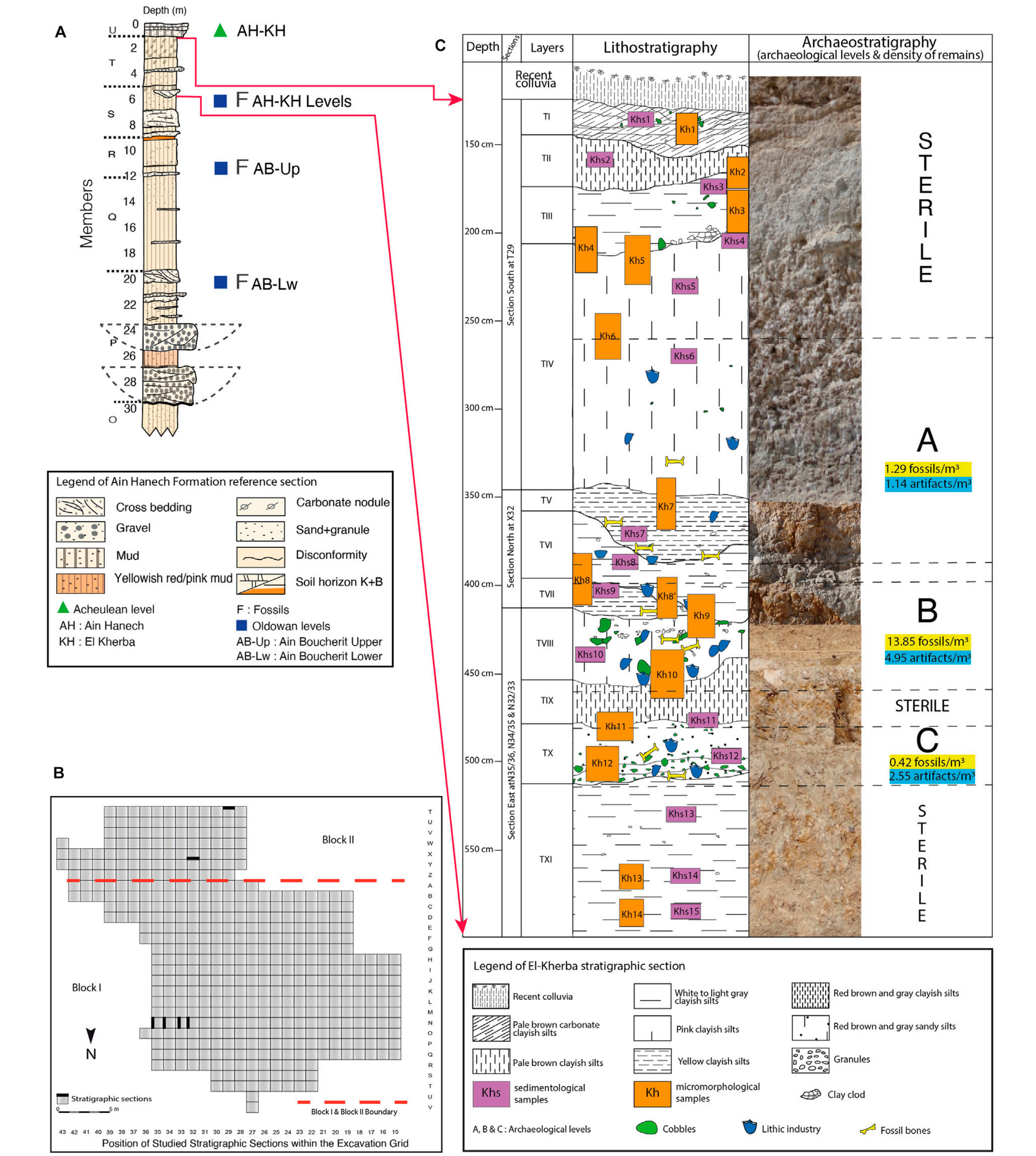

FIGURE 3 | El Kherba site stratigraphy including **(A)** position of El Kherba deposits within the Ain Hanech formation, **(B)** position of studied stratigraphic sections within the excavation grid, and **(C)** detailed stratigraphic profile and location of sampling for sediment and micromorphological studies.

inclusions (iron and manganese). The sedimentary features of the successive layers (TI–TXI), from top to bottom, are as follows.

Layer TI consists of pale brown (10 YR 8/3) homogeneous carbonated clayey silt, which is variably thick (19–27 cm), organized in sheets, friable, and strongly disturbed by rootlets from overlying colluviums; fissures that are horizontally oriented; few small-sized limestone gravels (~3 cm in diameter); and rare black flint granules. Layer TII is variably thick (15–30 cm) consisting of compact and indurated pale brown clayey silt (10 YR 8/3) and few flint granules. Layer TIII consists of 30 cm thick indurated white gray (7.5 R 7/0) clayey silt and some medium-sized (3–6 cm) limestone pebbles. Horizontal and vertical cracks caused its disintegration in thin plates, and cracked clay clods of various sizes (8–10 cm) appear at the base. Layer TIV is 1.10 m thick pink (7.5 YR 8/4) clayey silt with fine sands in its base. The color of the sediment is heterogeneous due to $CaCO_3$ spots of variable shapes and sizes (1–5 cm), the consistency is friable, and the texture is polyhedral, flint granules. Layer TV is variably thick (10–40 cm) and bowl shaped, which consists of light reddish brown clayey silt (5 YR 6/3) with some gray clay blots (7.5 R 7/0). Fine sand is more important than in upper layers; the consistency is friable and the structure is in prismatic blocks due to vertical cracks; presence of carbonated nodules (~1 cm in diameter); this layer is poor in coarse elements. Layer TVI is thicker on the distal ends (40 and 52 cm) than in the middle (23 cm), consists of gray clayey silt (7.5 YR 7/0), has low proportion of sand, is friable and in prismatic blocks, is dotted with $CaCO_3$ spots and with metal oxyhydroxides in the form of dendrites, and has rare coarse elements. Layer TVII is 40 cm thick. It consists of light reddish brown clayey silt (5 YR 6/3) and gray clay clods (7.5 R 7/0) with fine sand, is friable and in prismatic blocks, and includes metal oxyhydroxides as veneers and carbonate spots. This layer discontinues abruptly toward the west due to a phase of erosion caused probably by a brief intensity storm event. Layer TVIII is 0.45 m thick sandy silt with a large proportion of medium-sized (3–6 cm) and large-sized (6–10 cm) pebbles and granules representing 50% relative to the fine-grained fraction. It consists of small polyhedral blocks due to numerous vertical cracks and is friable and covered with metal oxyhydroxides in the form of spots and 4–5 cm thick layers, giving it variegated color made of gray (7.5 R 7/0) and reddish brown (5 YR 6/3). Layer TIX is 0.25 m thick gray (7.5 R 7/0) and reddish brown (5 YR 6/3) variegated clayey silt with a structure organized in polyhedral aggregates. It is friable and of heterogeneous color due to metal oxyhydroxides in the form of centimetric beds and $CaCO_3$ spots and contains rare granules. Layer TX is a light gray clayey silt (2.5 Y 7/0) extending over a homogeneous thickness (0.32 m), with the presence of Mn beds (~10 cm thick) and whitish $CaCO_3$ spots. The sediment is indurated and fissured, and abundant small (1–3 cm) limestone pebbles (some of which are altered) are primarily concentrated at the bottom of the layer representing more than 70% of the deposit. Layer TXI is 0.90 m thick friable clayey silt breaking down into small polyhedral blocks due to vertical and horizontal cracks. Its color is light reddish brown (5 YR 6/3) and gray (7.5 R 7/0) with some $CaCO_3$ spots but in a lesser proportion than in the upper layers; few granules are concentrated in the middle of the layer.

In terms of associated archeological remains, fossil bones and stone artifacts are contained throughout the stratigraphy in three distinct levels, namely, from bottom to top, C, B, and A (**Figure 3**) (Sahnouni et al., 2002). They are encased in layer TX for level C; in layers TVIII and TVII for level B; and in layers TVI, TV, and the lower half of TIV for level A. The thickness of levels C, B, and A is variable including 0.55 m (depth, −483 to −538 cm), 0.62 m (depth, −398 to −460 cm), and 1.27 m (depth, −260 to −387 cm), respectively. Level B is the thinnest, yet it encases the bulk of the archeological material (18.80 finds/m^3)) (**Figure 3**).

3 METHODS

3.1 Sedimentology

Of fifteen samples (**Figure 3**), thirteen unconsolidated sediments were analyzed. Each raw sample was previously dried at 40°C before quartering. The coarse elements (gravels and pebbles) were separated by water sieving to retain only the particles <2 mm (coarse and fine sands, silts, and clays). The latter were subject to a sedimentological analysis including grain size analysis, carbonate quantification, and pH measurement. However, a brief microscopic observation of the thin sections prior to the particle size analysis revealed the presence of micritic aggregates and localized areas slightly to strongly cemented by micritic calcite. Therefore, it was necessary to use a solution of hydrogen peroxide to destroy the organic matter and 10% diluted hydrochloric acid to remove the carbonates. Then, sodium hexametaphosphate at 5 g/l was added to the sediment that was ultrasonicated for 30 s. The grain size analysis of the decarbonated sediments was carried out wet with the granulometer Malvern Mastersizer 2000 laser diffraction particle size analyzer, using the wet technique because of the silty clayey texture of the samples. In our protocol, we favored the Fraunhofer approximation because it allows for the analysis of heterogeneous sediments with different refractive indices. To optimize the reproducibility of the results, four tests were undertaken on the same sample. The results show no variation in the data and display a perfect superposition of the graphs. The average of the different results was retained. The curve and the grain size parameters were acquired in digital form. The grain size distribution of the samples was processed with the GRADISTAT software (Blott and Pye, 2006).

For estimating the carbonate proportions by infrared spectroscopy, we favored the pellet preparation method because it allows for a quantitative analysis. The employed procedure is that by Fröhlich and Gendron-Badou (2002) that includes the following steps: 1) mechanical grinding of the raw sediment with agate mortar until particles <2 μm are obtained; 2) taking 1 g sample composed of 2.5 mg of ground sediment and 997.5 mg of KBr (potassium bromide), with 10–5 g accuracy; 3) homogenization of the mixture with agate mortar during 5 min; 4) pelleting of 300 mg of the mixture under 10 to 11 tonnes of vacuum pressure during 1:30 min; 5) steaming the pellets for 24 h at 100°C to evacuate atmospheric water; and 6) measuring with an infrared spectrometer.

The pH measurement is realized with a pH meter comprising an electrode and an electronic box. 20 g of <2 mm diameter raw sediment from each sample is diluted in 50 ml of distilled water. The solution is then subjected to magnetic stirring for a few minutes. After calibrating the pH meter with neutral (scale 7), acid (scale 4), and then basic (scale 9) buffer solutions, the electrode is rinsed with distilled water and then introduced

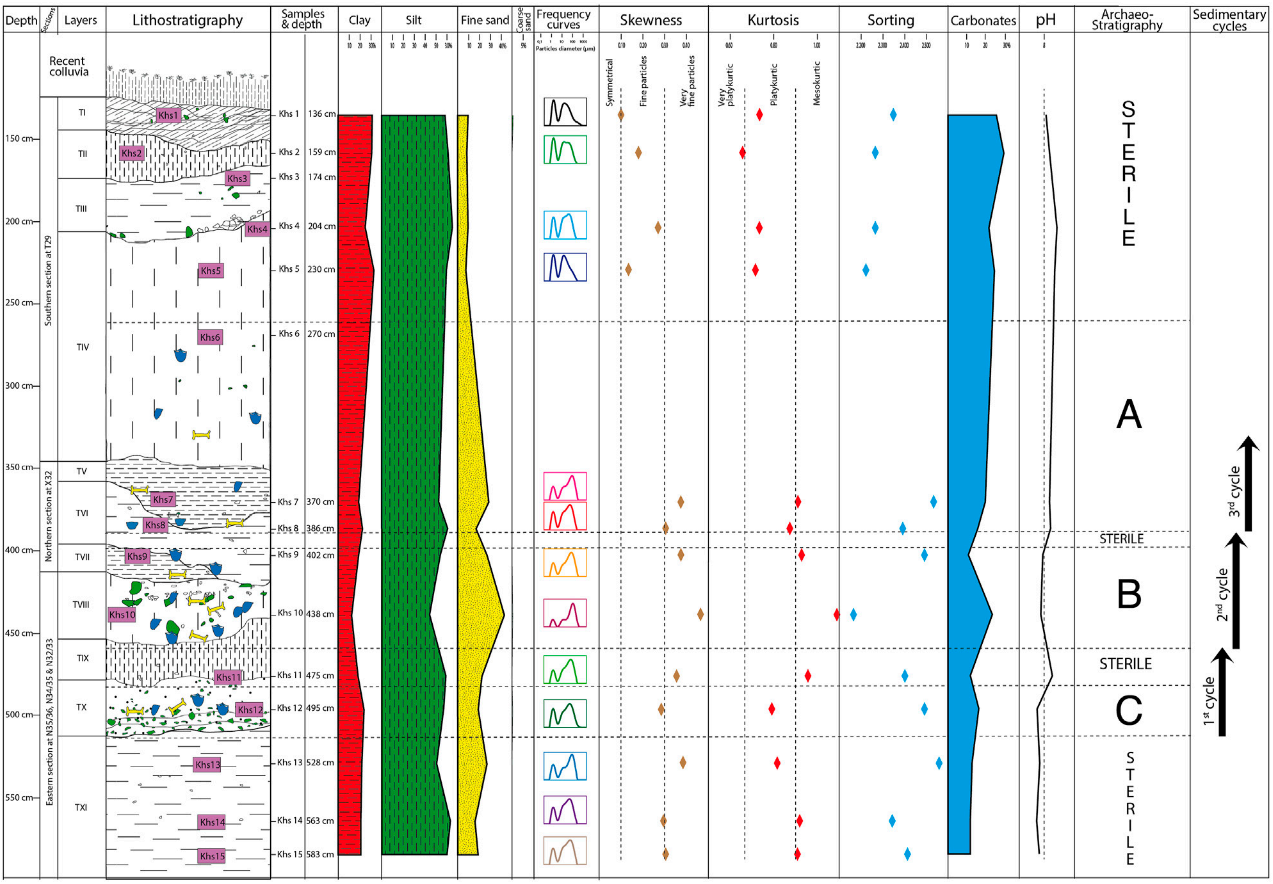

FIGURE 4 | Sedimentological results including grain size showing proportions of fine particles, frequency curves, kurtosis, skewness, sorting, carbonates, pH, and sedimentary cycles.

into the solution. The pH value is directly displayed on the electronic box screen.

3.2 Micromorphology

Fifteen micromorphological samples were collected throughout the El Kherba stratigraphic profile (**Figure 3**). The sampling procedure used is that of plaster blocks described by Courty and Fédoroff (2002), which prevents any disintegration of the sediment during its transport. In the field, the procedure consists of extracting samples in the form of blocks measuring 15 × 10 × 10 cm. The blocks can contain one or more stratigraphic layers depending on the thickness of the latter. All the visible faces of the block were plastered and labeled by site and number, stratigraphic position, and orientation. Once hardened, the blocks were removed, and their internal faces were plastered.

In the laboratory, the process developed by Guilloré (1985) was used to produce thin micromorphological sections. The blocks were opened on only one side, oven-dried at 25°C for 72 h, and cell impregnated with a mixture of polyester resin fluidized with styrene in a proportion of two-thirds/one-third, to which a few milliliters of the Butanox catalyst and 2–3 drops of an accelerator were added. They were indurated in an airy fume cupboard until the resin was completely consolidated. Each block was cut lengthwise into two parts using a diamond saw. While one part is archived as copy, the other part is cut into a 60 mm × 120 mm x 10 mm slab and mounted on a slide glass with polyester resin and thinned to 35–40 µm (for mineral transparency). A total of thirty thin micromorphological sections were made. They were first examined under a petroscope (which offers a wide field vision of the sample constituents) and then under the polarizing microscope at ×1.6, ×5, ×10, ×20, and ×63 magnifications. Plane-polarized light (PPL) and crossed-polarized light (XPL) were used for detailed description of the sediment microstructure and for taking microphotographs at various scales.

4 RESULTS

4.1 Grain Size, Carbonates, and pH Analyses

The particle size analysis reveals that El Kherba sediments are made up of a high proportion of silt–clay (80%). Sands, averaging 20%, are represented exclusively by fine sands (99%), while clays are significantly less abundant than silts (23 versus 57%) (**Figure 4**). The latter are relatively stable throughout the

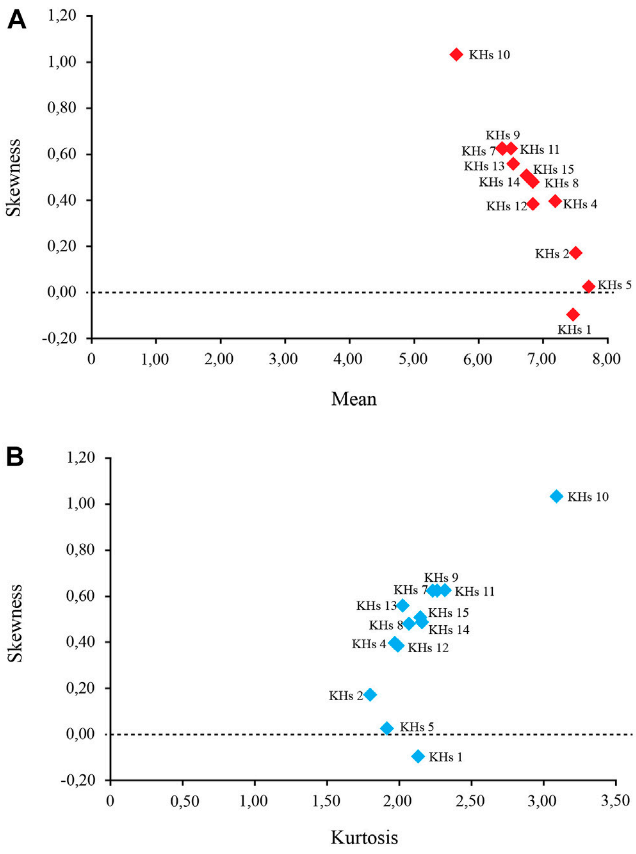

FIGURE 5 | Diagrams comparing indices (in phi), including **(A)** comparison of mean with skewness and **(B)** comparison of skewness with kurtosis.

stratigraphy, while the sands experience significant variations between the lower part of the stratigraphy (from base up to layer VIII) where they vary between 17 and 43% and the upper part (from layer VIII to the top) where they decrease to 8%. This reduction occurs mainly at the expense of clays, which gradually increase to reach 30% in the upper layers due to a change in the deposition dynamics. Based on Blott and Pye (2006) criteria, the grain size curves are bimodal in eleven samples and trimodal in the samples KHs 2 (layer TII) and KHs 10 (layer TVII). The kurtosis index ranges between 0.65 and 1.09. The highest values are in the lower part (from the base to −370 cm) showing mesokurtic and platykurtic curves. The lowest values are found toward the top part forming mostly platykurtic curves (except sample KHs 2 that is very platykurtic). According to Miskovsky and Debard (2002), all these curves reflect a mixture of one or more sediment populations. Asymmetry (or skewness) shows a tendency toward finest particles in the first half of the infilling and toward fine particles in the second half (**Figure 4**). Only sample KHs 1 presents a symmetrical curve. The sorting index, whose values are between 0.170 and 0.223, also subdivides the profile into two sets (**Figure 4**) and indicates a good sediment classification with particles increasingly calibrated toward the top. The ratio of the asymmetry (skewness) and the mean of the grains, on the scale of ϕ (**Figure 5A**), shows that all the samples, except KHs 1, have positive values. According to Friedman (1961), they correspond to sands of dunes or rivers. Yet, as these values are <1.49 ϕ, a dune origin is ruled out. The ratio of skewness and kurtosis also shows positive values (1.79–3.08 ϕ) and a wider distribution of kurtosis points (**Figure 5B**). These values also reflect sand from dunes or rivers (Friedman, 1961). Solely KHs 1 has a negative value, which is a sample from a level relatively rich in coarse sands (**Figure 4**). However, the composition of the sediments, consisting predominantly of fine particles (<40 μm), the notable proportion of fine sands (up to 43%), poor particles' sorting, and the presence of stratification suggest hydric deposition of the sediments. However, the presence in some samples of more than one mode does not rule out an eolian origin of the sands.

The carbonates are nodules of a few centimeters in diameter, or in the form of cement. Infrared spectroscopy analysis of the raw sediments indicates that their proportion varies between 11 and 30% with the lower part of the deposits being less supplied (**Figure 4**). Their evolution, which is close to that of fine sands in the lower half of the infilling, becomes, thereafter, parallel to that of the clays in the upper half. This concomitant evolution of carbonates and sands in the lower layers shows a common detritic origin of the two fractions, while in the upper layers, they are in a secondary position following the recrystallization of the calcite within the mass (see *Micromorphological Analysis*).

The sediments have an alkaline pH with minor values (7.66–7.94) in the lower levels of the infilling than in the upper levels (8.09–8.59) (**Figure 4**). Their evolution is related to carbonates, which allows carbonate stability (Karkanas and Goldberg, 2019) and creates favorable conditions for a good preservation of faunal remains (Stephan, 2000; Berna et al., 2004; Karkanas, 2010). Despite the alkalinity of the sediments, we note the presence of some organic residues, which require a humid environment and an acidic pH~3 (Fraysse et al., 2004; Shahack-Gross et al., 2004). This antinomy is explained by the contribution of water rich in calcium carbonate transforming the acidic medium into a basic medium (Shahack-Gross et al., 2004) and would have contributed significantly to the decomposition of organic matter (Karkanas, et al., 2000; Fraysse et al., 2009).

To sum up, El Kherba grain size data reveal a stability in the evolution of the proportion of silts and variations in those of sands and clays depending on the depth of the stratigraphic profile. These differences allow us to subdivide the profile into two sedimentation phases. The first phase, from the base to −370 cm, is somewhat high-energy deposit as it is formed of a coarse fraction of pebbles and granules along with a fine fraction comprising 56% silt and 24% sand. The second phase, which extends to the top of the profile, is relatively stable and characterized by more homogeneous sediments and a silty clayey texture (61% silt and 30% clay). The different parameters (kurtosis, skewness, sorting) confirm this subdivision with distinct values in the two parts of El Kherba stratigraphy suggesting two modes of deposition. The first mode characterizes its lower part that is silty–sandy with a high concentration of gravels and cobbles. These deposits correspond to alluvium of bottom load generated

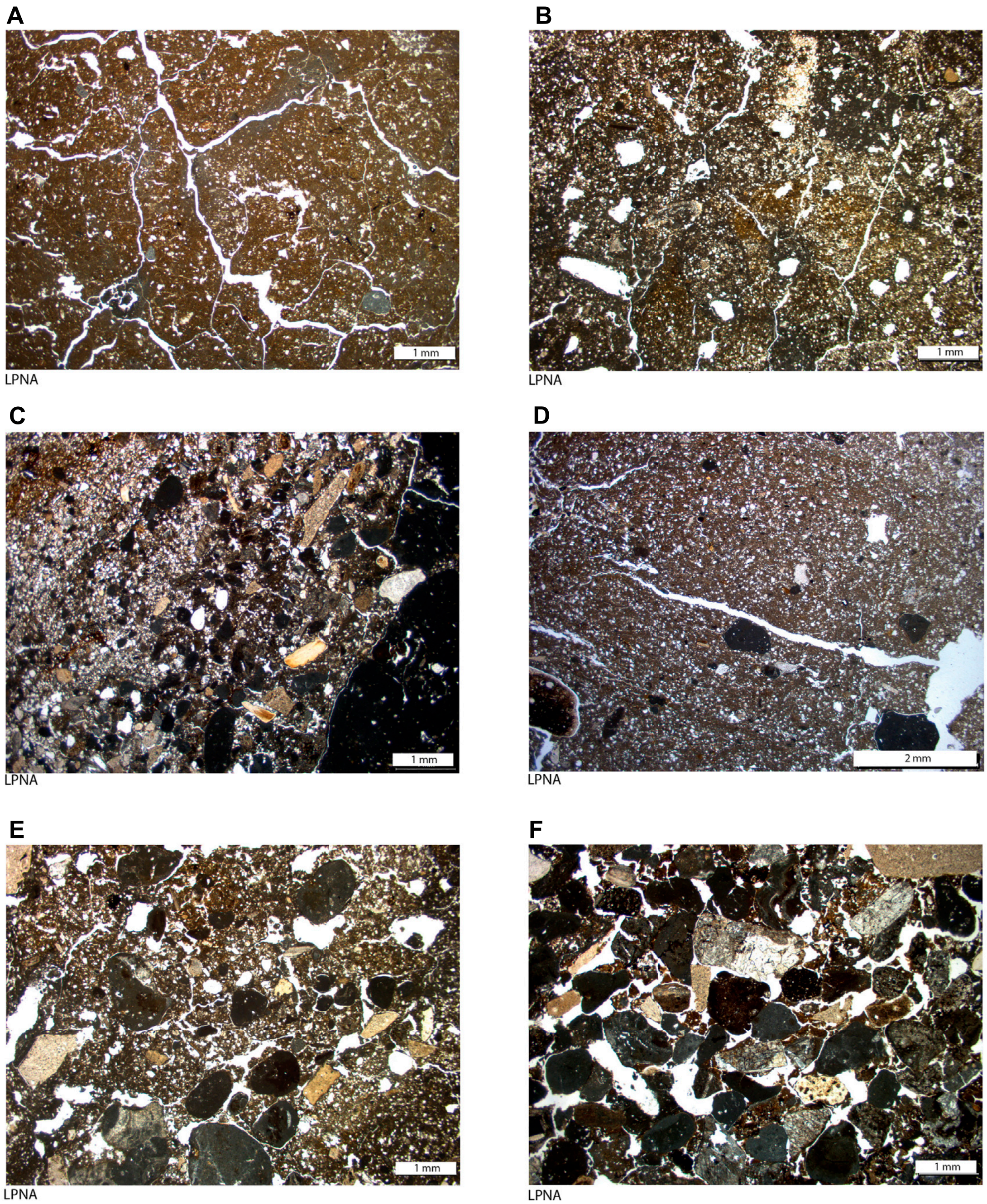

FIGURE 6 | Sedimentary facies including **(A)** clayey silty microfacies with a massive structure and subangular polyhedral blocks, separated by splits and deviated and interconnected cracks typical of the shrinking–swelling phenomenon (sample KH 1B, layer I); **(B)** a microstructure with subangular polyhedral blocks superimposed on a microstructure with channels invoking a rootlet biological activity (sample KH 3B, layer III); **(C)** microfacies with bedded microstrata of coarse and fine sands (sample KH 12H, layer X); **(D)** microfacies with compact silty–clayey–sandy lenses superimposed on silty–sandy lenses with a platy microstructure (sample KH 7B, layer V); **(E)** microfacies with unorganized and heterogeneous coarse particles with grain and micro-aggregate packing, plane voids, and porphyric distribution (sample KH 2H, layer II) and **(F)** with chitonic distribution (sample KH 12H, layer X).

by a high-energy regime. The second mode concerns its upper part, which consists of an exclusively silty clayey texture suggesting an attenuation of the intensity of the water regime with the deposition of fine particles. Fine-grained particles and the alternation of lenses of fine sands and silts (see *Micromorphological Analysis*) rather suggest their transport by low energy currents and their settlement by suspension during periodic flooding characteristic of floodplain setting, which is known to be deposited at lower flow speeds.

4.2 Micromorphological Analysis

The micromorphological features of the El Kherba sediments are summarized and comprehensively described with their paleoenvironmental implications, respectively, in **Supplementary Table S1** and Supplementary Text (**Supplementary Material**). Here, we highlight the results of the micromorphological study concerning the lithological facies and post-depositional development of the sediments.

4.2.1 Lithological Microfacies

Based on the micromorphological study, three lithological microfacies are recognized in El Kherba, which are repeated throughout the stratigraphic profile. The first microfacies is clayey silt with a massive structure approaching 85–95% of the total sediment. This high proportion of the fine fraction, unorganized and devoid of coarse elements, characterizes flood plain sediments deposited by suspension (Courty and Féderoff, 2002) and assumes a slow burial (Vallverdú et al., 2001). The texture of this facies also constitutes an impermeable layer conducive to water retention. As a result of its drying up during the dry seasons, a microstructure is formed with subangular polyhedral blocks, separated by planes and cracks deviated and interconnected slots (**Figure 6A**) typical of the shrinking–swelling phenomenon (Courty et al., 1989). When the biological activity is expressed, the microstructure with subangular polyhedral blocks then overlays a microstructure with channels (**Figure 6B**). The distribution is in both cases porphyric. Depletion pedofeatures are expressed by the loss of the fine fraction and the on-site concentration of the coarse residues. They are indicative of significant water circulation (Berger et al., 2012).

The second microfacies is made of bedded microstrata of coarse and fine sands (**Figure 6C**) or of compact silty–clayey–sandy microstrata overlaying sandy–silt lenses with a platy microstructure (**Figure 6D**). The plane porosity is sub-horizontal to horizontal and occurs at the junction of sandy and silty beds. The alternation of these microstrata with compact structures results from a change in water flow sedimentation by spreading in a calm environment generated by low-velocity runoffs. The preservation of these silty–sandy lenses is explained by the rapid burial of the sediments (Vallverdú et al., 2001).

The third microfacies is related to heterogeneous unorganized coarse particles illustrating the unexpected character of the sedimentation (Vallverdú et al., 2001). They denote an increase in the water regime and particle fining upward suggesting a diminution in the water velocity (**Figure 6C**). The microstructure is stacked with grains and micro-aggregates with plane voids. The distribution is often porphyric, that is to say, these elements are included in the fine matrix (**Figure 6E**). When fine material is piled up in the intergranular porosity or forms films around the particles (**Figure 6F**), the distribution is called chitonic. These coarse particles are clasts, rounded micritic aggregates, iron–manganese and carbonated nodules, and numerous terrestrial shell remains.

4.2.2 Post-Depositional Development

The pedologic processes that affected El Kherba sediments include cracking of deposits, coatings, recrystallization of carbonates, impregnation of metal oxyhydroxides, and rootlet bioturbations. Cracking of deposits corresponds to post-infilling restructurations. They can be structural, mechanical, or biological. When structural, the cracking of deposits characterizes the coarse layers. The mechanical movements are due to the plastic deformations of the matrix, which occur during the alternation of the wetting and drying phases (Courty et al., 1989). They generate a porosity with deviated planes in the clayey silty or plane accumulations in the bedded layers. Subsequently, the voids were filled, partially or totally, with fine sand (**Figure 7A**) or heterogeneous sediment aggregates (**Figure 7B**) coming from paleosurfaces or resulting from disturbance of existing layers. The biological porosity is caused by the development of rootlets.

The coatings concern voids and aggregates on the one hand and rootlet vughs on the other hand. The first are related to post-sedimentary illuviation (Jamagne et al., 1987) and are made up of colloids or silty particles. Colloids are of two types: limpid and dusty. Limpid colloids are microlaminated and cover the interior of voids (**Figure 8A**) or wrap minerals (**Figure 8B**). They come from the dismantling of paleostructures and are attributed to medium energy water circulation (Fédoroff and Courty, 1994), and their mode of deposition is mainly made by capillarity in an environment characterized by contrasted alternating wet and dry seasons (Fédoroff, 1997). When the colloids contain silty particles, they become dusty and brown (**Figure 8C**) suggesting higher water circulations (Fédoroff and Courty, 1994; Jongmans et al., 2001; Kühn et al., 2010) or leaching of the fine fraction (Curmi, 1987). The second type of coating deals with rootlet porosity and is characterized by a regular and compact coating, often parallel to the major axis of the vugh (**Figure 8D**). It can reach up to 300 μm in diameter and consists of a decarbonation residue resulting from the dissolution of limestone by the rootlets during their development (Favre, 1937; Lucas and Montenat, 1967; Jaillard and Callot, 1987). The papules (**Figure 8E**) are small fragments of limpid clay from old clay illuviations and integrated into the groundmass. Their fractionation is due to the alternation of shrinking–swelling cycles, which occur during the wet–dry seasons (Kühn et al., 2010).

The carbonates appear in the form of micritic calcite or millimetric nodules. The latter are exogenous and numerous in the lower stratigraphic layers, and their origin and evolution are comparable of those of sands (**Figure 4**) as a result of dismantlement of catchment areas and their subsequent transport. The micritic calcite is secondary. Its diffusion in the mass also evolves in the same direction as the silty clayey fraction and passes from borders lining some cracks and micritic aggregates of the lower part of the stratigraphic profile (**Figure 9A**) from partial to total impregnation of localized areas in the upper part (**Figure 9B**). The formation of this cement presumes a humid environment and a neutral to basic pH (Mallol et al., 2017) resulting from inputs of water rich in calcium

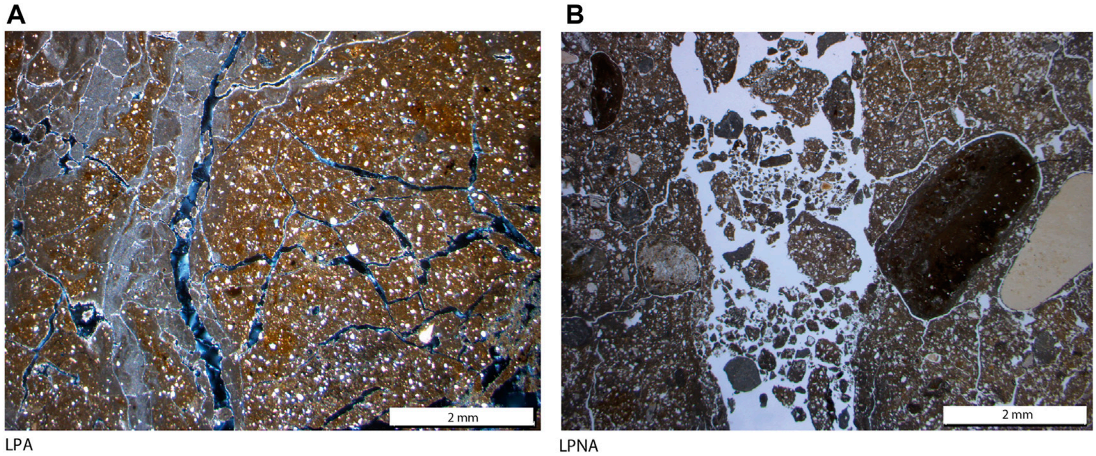

FIGURE 7 | Cracking of deposits including **(A)** partially or completely filled cracks with very fine sand (sample KH 5B, layer IV) and **(B)** deposition by illuviation or heterogeneous aggregates (sample KH 4B, layer IV).

carbonate combined with a low permeability of silty clayey layers. The saturation of the waters with calcium carbonates causes calcite precipitation when the water table dries out. The precipitation of calcite (Picq et al., 2002) accumulated in the form of micrite in the sediments and crusting around large mammal bones preserving them from erosion. As Freytet and Verrecchia (1989) pointed out, it is very likely that certain carbonate nodules can be derived from the fractionation of this micrite.

The impregnation of metallic oxyhydroxides is characterized by coatings (**Figure 10A**), by hypocoatings (**Figure 10B**) of voids, or in the form of edgings (**Figure 10C**). They reflect hydromorphic conditions, which involve redox cycles. These suppose 1) flooding of the deposits creating a reducing setting releasing iron and impoverishment of the zones (gray color of the matrix) and 2) during the drying up of the water, a transition to an oxygenated setting during which iron permeates the sediment (orange color of the matrix) (Courty et al., 1989). These recurring iron concentrations suggest the existence throughout the stratigraphic profile of several episodic phases of waterlogging and drying up of the deposits, and they are all more manifested when the sediment is fine-grained and less permeable and also participate in the process of iron reduction during their decomposition by micro-organisms (Karkanas and Goldberg, 2019). These features are detailed in the work by Le Drészen (2008) in the Sahel region, who equated the diffuse impregnation to dehydration of the sediments and the ferruginous borders to drying up of ponds. As for the double coatings, the ferri-argilanes, observed in rootlet voids (**Figure 10B**), are explained by the dissolution and leaching of carbonates from the fine fraction followed by iron precipitation (Massenet, 2008).

Bioturbation features are of moderate intensity represented by terrestrial shell remains and rootlets. However, rootlet bioturbations are more manifest and materialized by channels and pores, whether or not containing plant residues. These are calcified rootlets (**Figure 11A**) or rootlets (probably grasses) in the process of decomposition (**Figure 11B**). These rootlets consist of a mosaic of nested cells, roughly rounded or polyhedral averaging 25 µm in diameter. Organic matter is mainly expressed in the fine-grained layers, which implies that these have been saturated with water for at least part of the year (Jaillard, 1992). When this water regime evolves toward a reducing setting, there is iron precipitation and/or manganese oxides around the rootlet voids (Karkanas, 2010; Chen et al. (1980). Such features are present in certain voids of El Kherba sediments in the form of a single coating (**Figure 10A**) or superimposed on clay illuviations (**Figure 10B**). The plants from which these residues emanate usually develop under meadows, Mediterranean or alpine environments (Jaillard et al., 1991). However, an open savannah ecology is also in good agreement with the formation of these structures (Jaillard, personal communication).

5 DISCUSSION

The results of the sediment and micromorphological studies reported here allow us to discuss the implications of El Kherba sedimentary context in relation to the integrity of the Oldowan assemblages and their potential for preserving hominin behavioral information. As mentioned above, El Kherba sediments preserve traces of repeated Oldowan occupations, which are concentrated in three archeological levels, namely, from top to bottom, A, B, and C (**Figure 3**) (Sahnouni et al., 2002). Level C is correlated with the upper part of layer TXI and layer TX; level B is correlated with layers TVIII and TVII; and level A is associated with layers TVI, TV, and the lower half of TIV. Points of interest that need to be discussed here include 1) the type of depositional environment in which the hominin activities took place and 2) the impact of the depositional processes on the integrity of El Kherba Oldowan remains. With regard to the depositional environment, the grain size analysis of fine particles <2 mm clearly shows that the archeological levels are encased

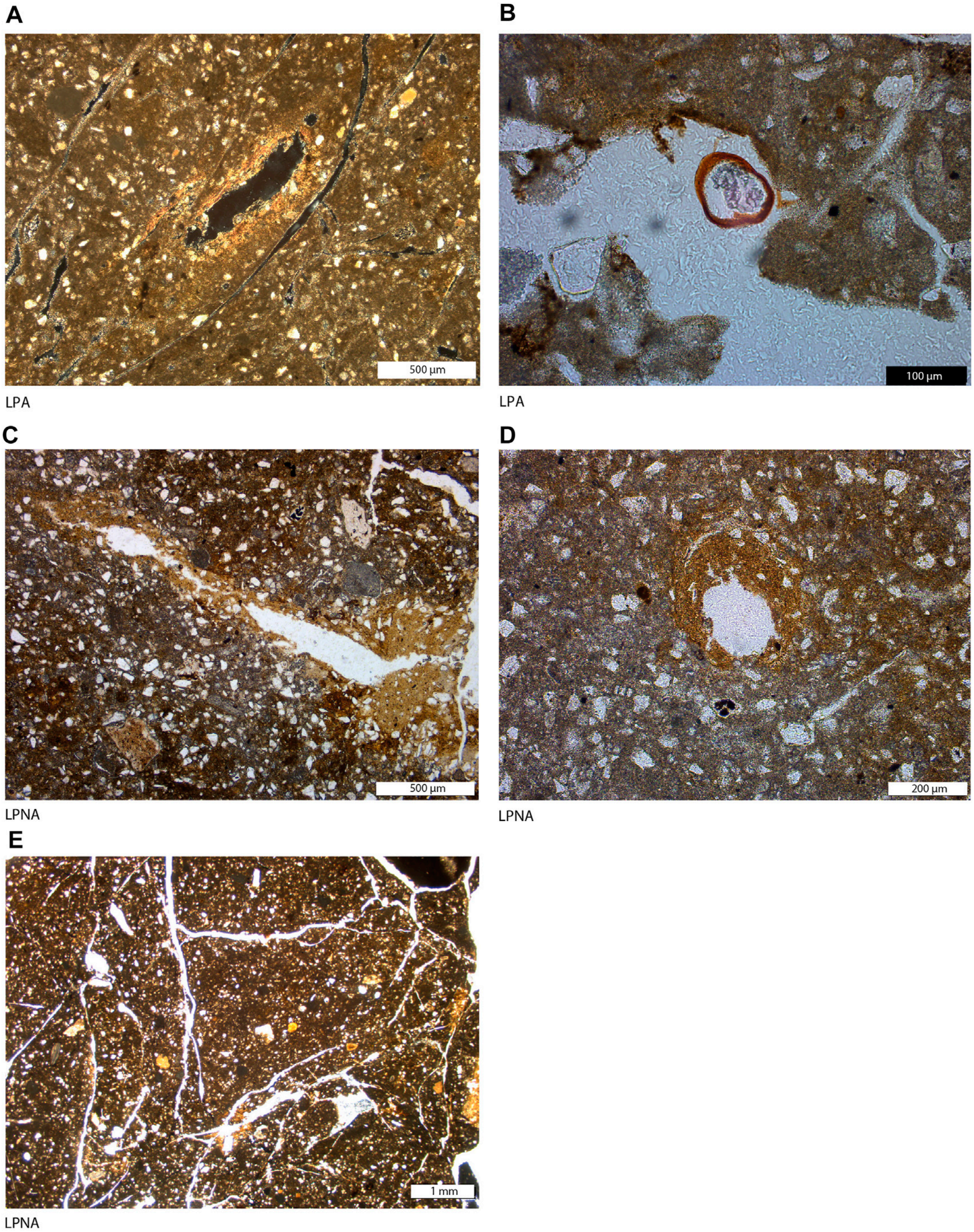

FIGURE 8 | Coatings including **(A)** microlaminated colloids covering the interior of voids (sample KH 6B, layer IV) and **(B)** surrounding aggregates that are to be linked to post-sedimentary illuviation (KH 4B, layer IV). **(C)** When the colloids contain silty particles, they become dusty or impure reflecting higher water circulations (KH 4B, layer IV). **(D)** In root porosity, the coatings are regular, compact, and often parallel to the major axis of the vugh formed by a decarbonation residue (sample KH 14, layer XI). **(E)** The papules are small fragments of limpid clay from old clayey illuviation and integrated into the basal mass (KH 6B, layer IV).

predominantly in fine-grained particles including silt, clay, and fine sand. On a microscopic scale, fine sands are often bedded, whereas the silts are massive and rarely microstructured. Thus, the archeological deposits were formed during sedimentary cycles with graded bedding in which each level begins with coarse sediments and is overlaid by finer particles or massive silts. This rhythmicity corresponds to hydro-sedimentary cycles where water flow was the main factor of transport and settling out of sediment grains. Notwithstanding the presence of coarse elements, the environment during the settling out of these deposits is temperate. It is widely

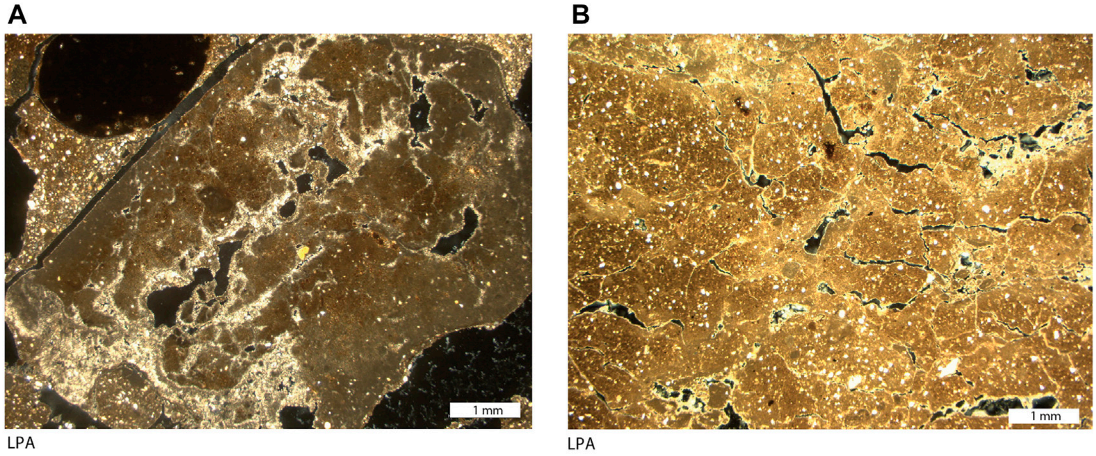

FIGURE 9 | Carbonates extend from **(A)** borders covering cracks and micritic aggregates in the lower levels (sample KH 11, layer IX) to **(B)** a partial to total impregnation of deposits toward the top (sample KH 1B, layer I).

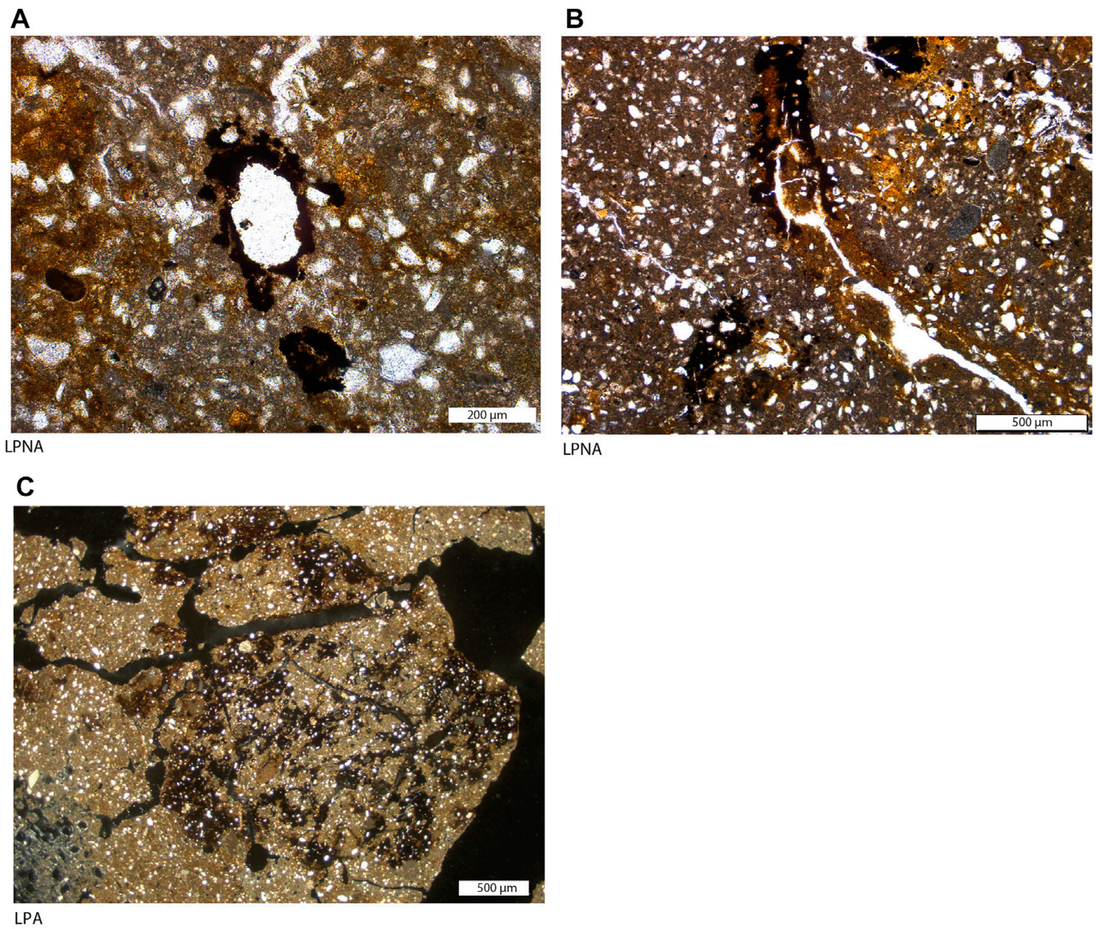

FIGURE 10 | Metallic oxyhydroxide characteristics, including **(A)** coatings (sample KH 14, layer XI) or **(B)** hypocoatings of void (sample KH 7H, layer IV) and **(C)** impregnations in the form of edgings (sample KH 10H, layer VIII). The types **(A, B)** reflect hydromorphic conditions which involved oxidation–reduction cycles. The double coatings (ferri-argilanes) observed in rootlet voids **(B)** are explained by the dissolution and leaching of carbonates from the fine fraction followed by iron precipitation.

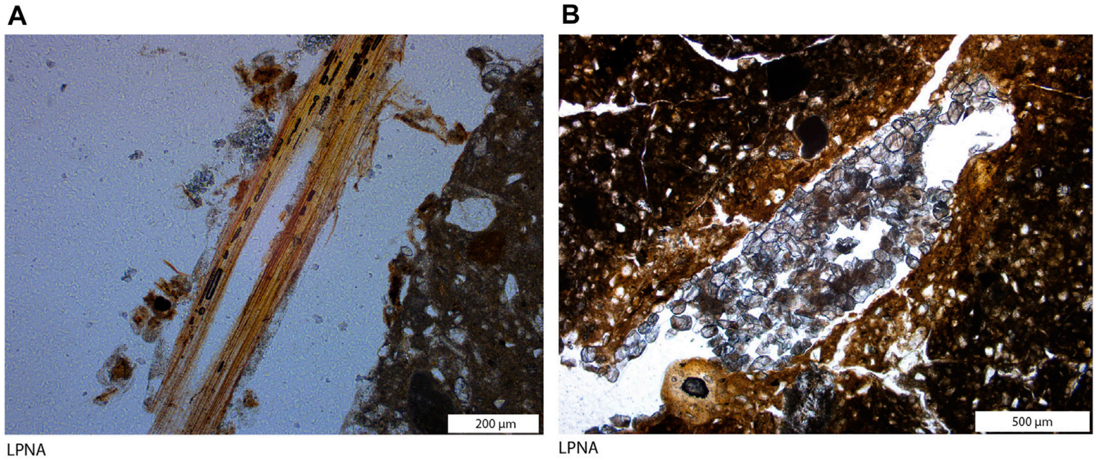

FIGURE 11 | Plant remains including **(A)** calcified rootlets (sample KH 9H, layer VI) and **(B)** rootlets, possibly of grasses in the process of decomposition (sample 6H, layer IV).

expressed by the predominance of fine-grained sediments, which represent the undeniable mark of deposition by suspension in a floodplain environment for the massive facies and by low runoff for the bedded facies. As for the levels rich in sands and granules, they signal secondary climatic oscillations characterized by an increase in precipitation during rainy seasons.

The decline in the proportion of sands from the base to the top of the infilling and their progressive replacement by silts and clays herald a gradual transition from a temperate climate to an arid one. This change toward a dry environment is supported by the observed variations in carbonate proportions. A fraction of the carbonate has been transported and deposited with the sands, as is the case in the archeological levels where the variations of the carbonates and sand fractions are parallel (e.g., in levels C and B). The rest of the carbonates emanate from the recrystallization of the calcite (e.g., level A), contained in these flooding silts, after the drying up of the water suggesting an arid environment. The change to an arid environment is corroborated by isotopic and faunal evidence (Sahnouni et al., 2011). For instance, isotopic analysis of El Kherba pedogenic carbonates shows a strong positive trend of increasing $\delta^{13}C_{PC}$ and $\delta^{18}O_{PC}$ values through time suggesting a temporal increase in C_4 vegetation and in aridification, respectively. The faunal evidence shows the presence in the upper levels of more hypsodont bovines, an increase in the abundance of equids, and the disappearance of small antelopes more adapted to a less open habitat.

In terms of site integrity, these sedimentary structures indicate that the burial of archeological remains in fine particles preserved them from biodegradation and hydraulic disturbance forces. The impact of soil processes on sediment deposition must have been limited or of lesser intensity as shown by the microlaminations. Based on the sedimentary evidence, overall, the El Kherba archeological occurrences appear to have been buried in a primary sediment context with minimal rearrangement. Other lines of evidence, including the physical aspects of the archeological occurrences and their spatial disposition in the site, substantiate to a great extent the integrity of El Kherba Oldowan site (Sahnouni et al., 2013). For instance, the bone weathering patterns [primarily stages 1 and 2 based on criteria by Behrensmeyer (1978)] indicate that animal bones were exposed to climatic conditions for less than 3 years prior to burial. The faunal assemblage comprises all categories of skeletal elements, making hydraulic sorting unlikely. In addition, fossil bones and stone artifact show neither a preferred orientation nor a high dip (Sahnouni et al., 2013) (**Supplementary Figures 3C, Da,b**). Similarly, the lithic assemblages are macroscopically fresh and coherent and include cores, debitage, and small fragments (<2 cm of maximum dimension) (**Supplementary Figure 3A**). The debitage and small fragments are overwhelmingly represented relative to cores mimicking experimental stone tool assemblages generated by Schick (1986) (see **Supplementary Figure 3B**). In addition, a number of stone tools preserved usewear on their edges (Sahnouni et al., 2013). If these stone tools have been subject to water rearrangement, the usewear would have not been preserved. However, the preservation of the archeological material is not homogeneous across all the site. As a matter of fact, some bone fragments show various degrees of polish damage on their surfaces. These occur particularly in level B corresponding stratigraphically to layer TVIII in which a quantity of fine sands and a small amount of coarse sands are present. They might have been introduced from close distance by medium energy currents in the course of channel aggradation. According to Behrensmeyer (1982) and Behrensmeyer and Chapman (1993), abraded bones are usually found within floodplain deposits as a result of channel lateral aggradation and bone reworking through bank erosion in a fluvial system consequently to intense and intermittent rain precipitations.

6 CONCLUSION

This paper presented the sedimentary context of the Oldowan site of El Kherba (Ain Hanech, Algeria) involving sediment and micromorphological studies. The following tentative conclusions are proposed.

The studies offered a detailed assessment of the sedimentary processes that took place in the accumulation of the Oldowan remains. For instance, the grain size analysis shows that the sediments encasing El Kherba fossil bones and stone tools are primarily fine-grained particles, mainly silt and clay. Likewise, the micromorphological study reveals massive sediment structures made primarily of fine particles. The massive sediment structure is suggestive of water retention and supersaturation of the deposits making them impermeable. This type of sediment size characterizes flood basins which are known actually to be deposited at lower flow speeds. The El Kherba floodplain environment created favorable conditions for a rapid burial of animal bones and stone tools, and ultimately preserving valuable archeological data that allow us to reconstruct hominin technological and subsistence behaviors dated back to 1.8 Ma. As a matter of fact, El Kherba excavations yielded well-preserved faunal and lithic assemblages with evidence showing a clear causal link between Oldowan stone technology and processing of large animal carcasses for meat acquisition by early hominins (Sahnouni et al., 2013). The lithic assemblage incorporates all the technological stages of the sequence reduction for the manufacture of Oldowan tools and used artifacts. The bone assemblage includes all anatomical skeletal elements and several cut-marked and hammer-stone percussed bones.

The studies also contributed to the reconstruction of the prevailing environments during which early hominins carried out their behavioral activities. The microscopic study of the sediments indicates that El Kherba archeological levels were accumulated in fining-upward sediment cycles in which each level starts with coarse particles and ends up with massive silts or micro-bedded sand or silty sand. From a paleoenvironmental point of view, the sedimentary evidence overall suggests a temperate climate with increasing rainfall during rainy seasons. The decline of sands and the high proportion of carbonates from layer VI and upward is indicative of a gradual change from humid to arid environment. This environmental change is consistent with faunal and isotopic evidence of increasing open landscape and aridification documented throughout the El Kherba stratigraphic profile, particularly from archeological levels B to A with impact on early hominin foraging activities. Isotopic evidence suggests that level B was predominately closed habitat with C_3 vegetation probably in riparian settings with networks of fluvial channels (Sahnouni et al., 2011; 2017). In such habitat, rivers would have provided rocks for stone tool manufacture and would have attracted game for meat acquisition by early hominins. In contrast, the evidence suggests that, during level A, the environment was increasingly open and arid. An arid habitat would have offered much less opportunities for accessing water and food supplies due to their scarcity on the landscape. The impact of the environmental change on early hominin foraging capabilities is likely reflected in the abundance of stone tools and fossil bones in level B and their paucity in level A.

From a methodological point of view, to the best of our knowledge, this is one of the rare comprehensive inquiries into sedimentary processes that have been fully integrated in North African Lower Paleolithic studies. This sedimentary context investigation has been undertaken within a multi-perspective examination of the processes that took place in the formation of El Kherba site, which also includes taphonomic grades of bones and patterns of stone artifact concentration. This multi-perspective approach has become a standard procedure to identify the different agencies playing a role in the formation of a Paleolithic site prior to any archeological interpretation of fossil remains and stone artifact concentration patterns. The sedimentary context is a line of evidence of great interest in appraising formation processes as it provides assessment regarding possible disturbance of archeological occurrences, and it contributes to reconstructing the environment in which the hominin activities took place. The results of the sedimentary matrix analyses are consistent with those of bone taphonomy and concentration of artifacts converging to the same conclusion, that is, El Kherba Oldowan assemblages were accumulated in the primary sedimentary context although minimal rearrangement of remains might have occurred (Sahnouni et al., 2013). In addition, the sedimentological and micromorphological results are also coherent with faunal and isotope evidence regarding El Kherba paleolandscape reconstruction and environmental change (Sahnouni et al., 2011).

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, and further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

SA and MS conceived and designed the study. All authors contributed to the field investigation and to the writing of the manuscript (original draft preparation, review, and editing). MS and ZH were responsible for the project administration. All authors have read and agreed to the published version of the manuscript.

FUNDING

This research was funded by UMR7194 (CNRS, MNHN) and through grants awarded to MS grant PGC 2018-095489-B-100 by MCIN/AEI/10.13039/501100011033 and MINECO (HAR 2013-41351-P)], CNRPAH (Algeria), The L.S.B. Leakey Foundation (San Francisco, CA, United States), the European Research Council (FP7-People-CIG2993581) (Belgium), and the Stone Age Institute (Bloomington, IN, United States).

ACKNOWLEDGMENTS

The authors thank the Algerian Ministry of Culture for the research permit; Centre National de Recherches Prehistoriques, Anthropologiques et Historiques (CNRPAH), the Wilaya of Sétif, the municipality of Guelta Zerga, and the University of Sétif 2 (Algeria) for administrative and logistic support during fieldwork at El Kherba; the UMR 7194 sedimentological laboratories (Paris, France) for carrying out the sedimentological and micromorphological analyses, and Xavier Gallet of the same for pellet preparation and for the infrared spectra reading; and CENIEH (Spain) staff Beatriz de Santiago Salinas and María José de Miguel del Barrio for administrative support to MS.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2022.893473/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The Acheulean of the Upper Guadiana River Basin (Central Spain). Morphostratigraphic Context and Chronology

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OPEN ACCESS

Edited by:
Marie-Hélène Moncel, Director of research CNRS-MNHN, France

Reviewed by:
Alberto Saez, University of Barcelona, Spain
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Specialty section:
This article was submitted to Quaternary Science, Geomorphology and Paleoenvironment, a section of the journal Frontiers in Earth Science

Received: *03 April 2022*
Accepted: *03 June 2022*
Published: *24 June 2022*

Citation:
Santonja M, Pérez-González A, Baena J, Panera J, Méndez-Quintas E, Uribelarrea D, Demuro M, Arnold L, Abrunhosa A and Rubio-Jara S (2022) The Acheulean of the Upper Guadiana River Basin (Central Spain). Morphostratigraphic Context and Chronology. Front. Earth Sci. 10:912007. doi: 10.3389/feart.2022.912007

In the upper basin of the Guadiana River, especially in the sectors drained by its right-bank tributaries, the Bullaque and Becea rivers, important concentrations of Acheulean and Mousterian industries can be found in a superficial position. These industries have provided series containing tens of thousands of pieces. Deposits in stratigraphic position have also been identified, related to the fluvial terraces of the Guadiana and Jabalón rivers and some tributaries. Within the sector studied, in the province of Ciudad Real, the position of these deposits is related to alluvial fans developed on the slopes of the immediate reliefs. These fans, mainly composed of Lower and Middle Ordovician quartzite gravel, were eroded in their distal positions by the Bullaque and Becea rivers, forming very low terraces on which large concentrations of Acheulean and Mousterian lithic industry can be found. El Sotillo, the only known stratigraphic site in the area, was excavated in 2017–2019 and consists of several levels with Mousterian and Acheulean industry. We present the technological characteristics of the main Acheulean assemblage recognised at this site, for which numerical dates have been obtained placing its chronology in the second half of the Middle Pleistocene. The location of these sites, in surficial position and El Sotillo, allows us to recognise a territorial space with specific geographic characteristics and a very significant human impact.

Keywords: Iberian Peninsula, Guadiana basin, lower Palaeolithic, Acheulean, lithic technology, middle Pleistocene, luminescence dating, Palaeo-landscape

1 INTRODUCTION

The upper course of the Guadiana river - inland Iberian Peninsula- (**Figure 1**), in the Paleozoic regions of the south-eastern Montes de Toledo and the volcanic territory of Campo de Calatrava, has one of the highest concentrations of Acheulean and Mousterian sites of the Atlantic drainage basins of the Iberian Peninsula. Most of them are surface sites (Vallespí et al., 1979 and 1985; Santonja and Villa, 2006),

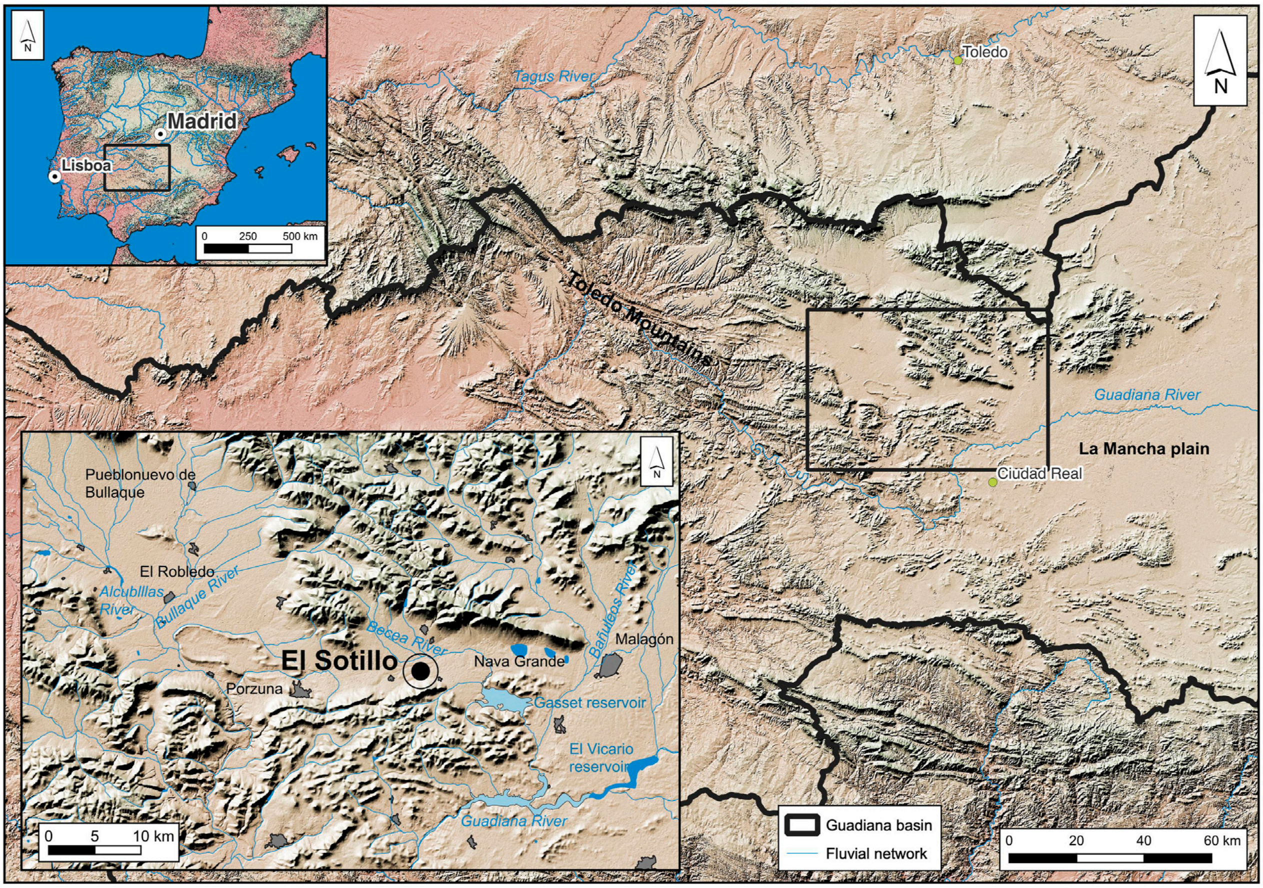

FIGURE 1 | Location of El Sotillo in the central-southwestern area of the Iberian Peninsula, and in the south-eastern sector of Montes de Toledo. In the bottom-left inset, the Acheulean site of El Sotillo is framed to the north and south by Palaeozoic hills with quartzite rocks, in the Porzuna-Malagón depression. Map made with data layers provided by the CNIG.

although some are in stratigraphic position (Santonja and Pérez-González, 2002), among which the site of El Sotillo, excavated in 2017–2019, stands out. Research carried out in recent years has focused on some of the few sites with series of lithic industries in stratigraphic position and includes a detailed study of the composition and technical features of the lithic industry. Our contribution includes a morphological and sedimentological characterisation of the fluvial and alluvial deposits bearing archaeological artefacts in order to understand some "taphonomic" features of the archaeological site.

In the regions of Montes de Toledo and Campo de Calatrava, both in the Guadiana basin, the fluvial networks and their terraces had barely fit in the landscape during their evolution throughout the Quaternary; highlighting the quartzite reliefs and their slopes covered with screes and extensive alluvial fans at the foot of the hills. The surficial Palaeolithic assemblages are a constant feature of the landscape of these regions (Santonja, 1976; Santonja and Pérez-González, 2002). The characteristics of these sites are relatively homogeneous, with a series in which cores and knapped products largely dominate, and a negligible component of shaped and retouched tools. The clearly recognized Levallois technology has been fundamental in identifying several of these sites as Middle Palaeolithic, although the difficulties in establishing chronologies or in identifying functional aspects have led to little interest in their study, despite some notable works (Martín Blanco et al., 1995; Jiménez et al., 1996).

In the locality of Porzuna, within our study area (**Figure 1**), an important group of sites on the +5 m terrace of the Bullaque River has been studied. In this area, a series of tens of thousands of quartzite pieces were previously collected on the surface, with some of them being conserved in the Museum of Ciudad Real, including heterogeneous materials from the Acheulean and Mousterian periods (Vallespí et al., 1979 and 1985). Another unique singular site is El Sotillo, at Malagón (**Figure 1**). This site displays complex stratigraphy, identified in 1983 by local researchers and mentioned in subsequent studies (Ciudad Serrano 1986; Santonja and Pérez-González 2002; Gómez Laguna et al., 2010; Arroyo and de la Torre, 2013; Arroyo et al., 2019).

There are other known -not studied here- Acheulean sites in stratigraphic position on the fluvial terraces of the Guadiana and Jabalón rivers. In the area where these river courses meet, a system of terraces has been recognised at levels of +45–50 m, +40–43 m, +31–33 m, +25-27, +19–21 m, +10–12 m, +7 m and

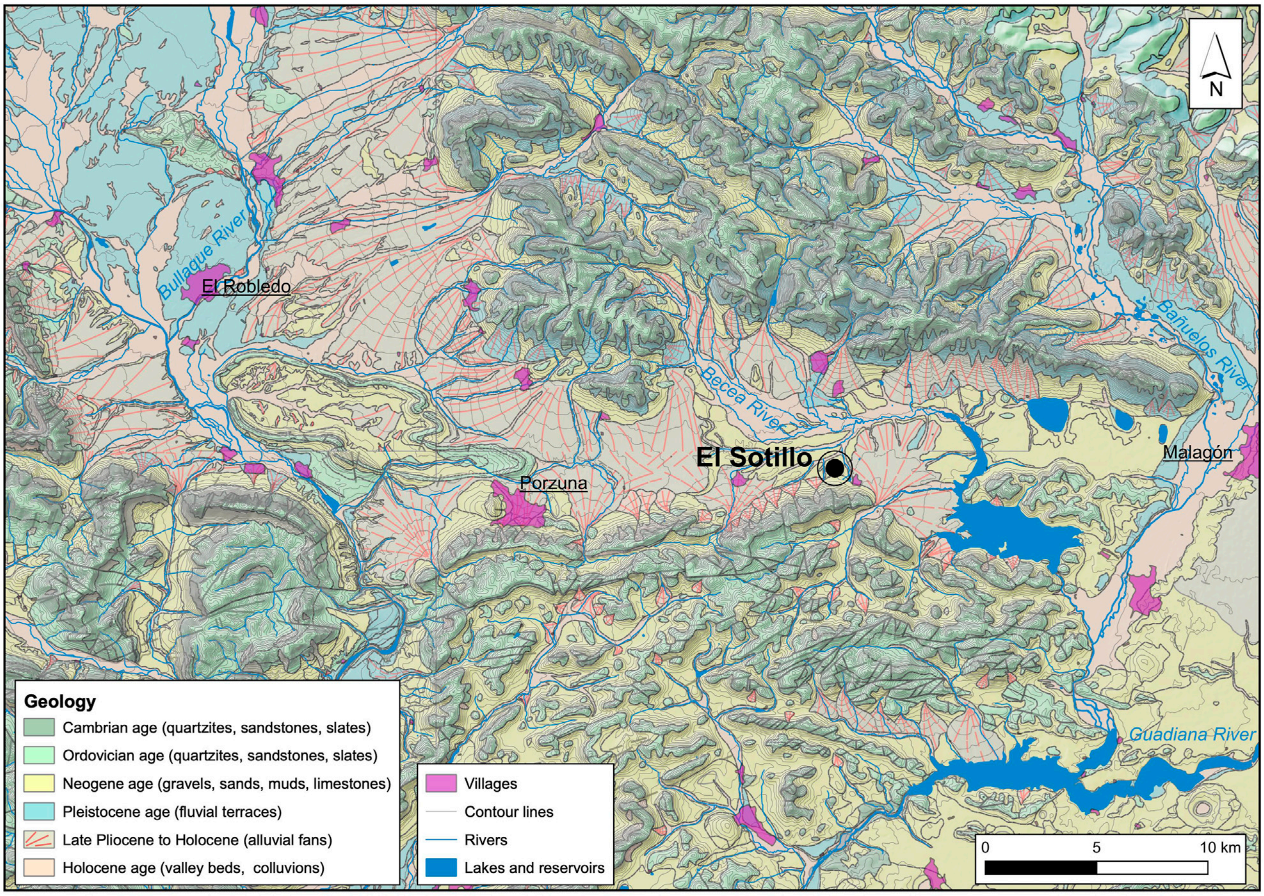

FIGURE 2 | Geological framework of the El Sotillo site (645 m. a.s.l.) in the Porzuna - Malagón synclinorium, with the Malagón quartzite hill (1070 m. a.s.l.) to the north and the El Sotillo sierra (890 m. a.s.l.) to the south. The Porzuna - Malagón synclinorium is crossed from W-E by the Becea River, a tributary on the right bank of the Bañuelos River, which is, in turn, a tributary of the Guadiana River. Map made with data layers provided by IGME.

+2–3 m (Pérez-González, 1982). The levels, at +10–12 m and +7 m, contain Acheulean industrial assemblages at different points along both rivers (Santonja 1981; Santonja and Pérez-González 2002; 2010).

In order to extend our knowledge of the regional Palaeolithic, between 2017 and 2019, we carried out three excavation seasons at the El Sotillo site. These allowed us to identify two levels with Acheulean lithic industry and another with Mousterian lithic industry, all three with no preserved fauna. In 2021, our work focused on the municipality of Porzuna, to verify whether any Acheulean or Mousterian industry was present at the sites in a stratigraphic position and to define the position of the sites from a morpho-stratigraphic perspective.

2 THE SITE OF EL SOTILLO. MATERIALS AND METHODS

2.1 Regional Geomorphological Context

The El Sotillo site is located within the Palaeozoic synclinorium of El Robledo-Porzuna-Malagón, a large Variscan structure forming an extended depression in the NW-SE direction, draining southwards, currently integrated into the Guadiana basin (**Figure 2**). It is located at the foot of the Sierra de El Sotillo (890 m. a.s.l.), with white orthoquartzites of Lower Ordovician age. To the north, the immediate landscape is dominated by the hills of La Fuenluenga and Malagón (1070 m. a.s.l.), also quartzitic, of the same age and lithological composition.

The upstream action of the rivers on the right bank of the Guadiana barely affects the territory of the previously mentioned synclinorium. Bullaque River conforms an anastomosed channels network crossing a 2–10 km wide alluvial plain (**Figure 2**). The *raña* -the name given to quartzite fan deposits, usually of large planar dimensions, from the Pliocene-Lower Pleistocene and prior to the first fluvial terrace of the current networks-is found in these sectors at +10–12 m above the alluvial plains of the Alcubilla and Bullaque rivers. Downstream from the area where the Bullaque and Guadiana meet, a more developed sequence of terraces can be observed, with levels at +2–3 m, +6–10 m, +12–14 m, +15 m, +20–22 m, +40–45 m and +60–65 m, with the *raña* at +80 m (Piles et al., 1986; Portero et al., 1986; Ramírez Merino et al., 2000).

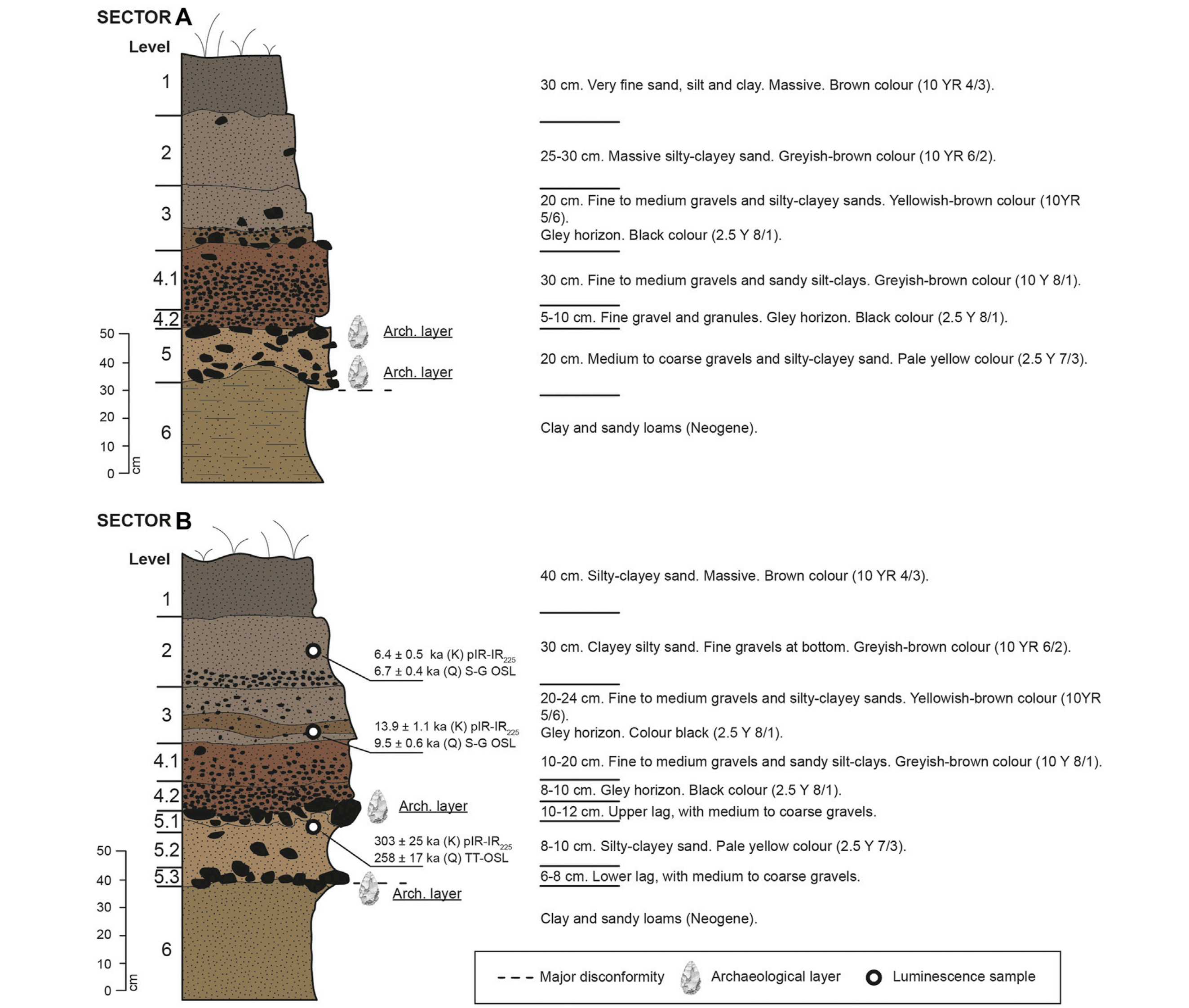

FIGURE 3 | Stratigraphic columns of sectors A (above) and B (below) of El Sotillo.

In the eastern sector of the El Robledo synclinorium, on the Malagón meridian, in the Bañuelos River we have recognised a geomorphological unit similar to that of the Bullaque River. It presents an extensive alluvial plain crossed by multiple fluvial branches and two terraces at +2 m and +6 m until it flows into the Guadiana River (El Vicario reservoir, **Figure 1**). The Becea River and the streams of its drainage basin have hardly any impact on its substratum, a geodynamic situation derived from the almost non-existent encasement of the base level imposed by the Guadiana River at the western end of the Plains of La Mancha. Another decisive factor in the scarce incision of the fluvial network is related to the excess of available coarse load, inherited from the reliefs draining from the Montes de Toledo, and which ends up favouring the formation of extensive alluvial plains and anastomosing channel morphologies, as is the case of the Bullaque and Bañuelos rivers.

The Becea River is about 5–6 m below the Raña and 15–16 m in the lower surface of the Plain of La Mancha. It is a formation with sandy-silty-clay carbonate facies at the base and laminar crusts, slightly less than 1 m thick at the top. This morphostratigraphic unit is preserved in the vicinity of the El Sotillo site (**Figure 2**).

2.2 El Sotillo Stratigraphy

The El Sotillo site has a 1.5 m thick stratigraphic sequence, and it contains Acheulean and Mousterian industries and rests directly on the Tertiary (Neogene) substratum. From a geomorphological point of view, it is located on the NW limit of the El Sotillo-Raña fan, associated with ancient fluvial courses coming from the Lower Ordovician quartzite hills, which produced deposits particulate material from gravel to silt-clay. Currently, the shallow El Sotillo stream, runs over the site, eroding it locally.

The recognised stratigraphic sequence at El Sotillo, sectors A and B, which are 20 m apart (**Supplementary Figure S1**), displaying common sedimentary characteristics. The fluvial deposits recognised in both sectors are accumulated on an erosive surface affecting the Neogene substratum (**Figure 3**). Five levels have been differentiated. The oldest (level 5), which carries bed load gravels, has Acheulean industry. Levels 4, 3 and 2 correspond to fluvial sediments of Holocene age, according to the dates obtained and presented in detail in the following section. Level 1 is an overflow deposit from the present-day El Sotillo channel. There is no record of lithic industry for the upper levels from the 4.2 to 1.

The lower terminus (level 5) carries larger clastic elements (between 10–12 cm and a centile or maximum size of 17 cm). Two concentrations of coarser materials (lag deposits) are distinguished at the top and at the bottom, both with industry, separated by sandy-clay facies. The lower one can be interpreted as a fluvial bar and the upper one corresponds to a second reactivation surface due to a higher water flow. The levels 4, 3 and 2 are composed of fine to medium size gravels (between 1-2 and 6 cm, measured at the major axis of the clast), that grades upwards to silts and clays indicating a progressive loss of energy. Level 1, with the highest percentage of fine and medium sand, represents over-flow deposits of the current channel, and according to the available chronologies of the different levels of the El Sotillo deposit, they have an intermittent activity separated by thousands of years.

Levels 5 to 2 are characterised edaphically by gleying pedological processes throughout the profile. It contains hard black nodular concentrations of MnO_2 up to 1 cm in diameter, particularly at the bottom of levels 3 and 4.2. The poor drainage, both laterally and vertically, is due to the low dip of the fluvial plain and the low permeability between the different levels, as they contain high percentages of silts and clays (60–70%).

The stratigraphy of Trenches C and D (**Supplementary Figure S2, S3**), from top to bottom, starts with a 40 cm thick anthropogenic colluvium, made up of soil disturbed and partially removed by heavy machinery, probably from the piping works (2008-2009) from the Torre de Abraham dam to the Gasset reservoir.

Next, in abrupt contact, follows level 2T, which is a layer 18–20 cm thick and contains Mousterian industry. It is composed of fine sands and silt-clays, with a massive internal structure and a brownish-dark brown colour (7.5 YR 4/4). This layer is in flat contact with the inferior level 3, which is 45 cm thick, made up of silt-clays and sand, more abundant on its base, together with irregularly distributed coarse clasts, sometimes grouped in the form of 'nests'. This level also contains Mousterian industry and is affected by a pedological process of clay illuviation; it has a strong polyhedral structure and a yellowish-red colour (5 YR 5/6). Level 4 contains Acheulean industry. It has a variable thickness of 5–25 cm and is composed of sands and fine gravels in which scattered coarse gravels appear; it is in erosive contact with the clayey Neogene level 5. Levels 4 and 5 show very accentuated hydromorphic soil conditions, similar to those observed in sectors A and B.

2.3 El Sotillo Luminescence Dating

Luminescence dating was conducted at the University of Adelaide's Prescott Environmental Luminescence Laboratory. Three luminescence samples were collected from Levels 5, 3 and 2 in excavation area B (**Figure 3**). Sample STL17-1 was collected from Level 5, within a 10 cm-thick clay-rich sediment layer sitting atop Miocene clays; sample STL17-2 was collected 30 cm above sample STL17-1, from the overlying Level 3, which is composed of fine sands and gravels; and the uppermost sample, STL17-3, was collected 35 cm above sample STL17-2 from Level 2, a floodplain deposit composed of fine sands with small gravels at the base. Post infrared (IR) IR stimulated luminescence (pIR-IR) dating of coarse K-rich feldspar grains was applied to all samples (Buylaert et al., 2009; Arnold et al., 2015). Additionally, single-grain optically stimulated luminescence (OSL) of quartz grains (Arnold et al., 2016) was applied to STL17-2 and STL17-3, as preliminary screening revealed that the burial doses of these two samples lie within a range that is generally suitable for conventional OSL dating (Arnold et al., 2015). STL17-1 exhibited a significantly higher burial dose estimate in preliminary screening tests, hence it was necessary to apply single-grain thermally-transferred OSL (TT-OSL) of quartz grains instead of replicate single-grain OSL to this lowermost sample (Arnold et al., 2015).

Sample preparation procedures, instrumentation, dose rate estimation, equivalent dose (D_e) measurement protocols, and luminescence characterisation results are detailed in the **Supplementary Material**. Samples were prepared using standard procedures under subdued red lighting to isolate the coarse (90–125 μm) K-rich feldspar and (212–250 μm and 90–125 μm) quartz fractions (see **Supplementary Material** for details). Dose rate evaluations were undertaken using a combination of *in situ* gamma-ray spectrometry and low-level beta counting (see **Supplementary Material** for details). Gamma spectrometry data was analysed using the "windows" method described in Arnold et al. (2012) to obtain concentrations of K, U and Th for gamma dose rate evaluations. Dose rates were calculated using the conversion factors of Guerin et al. (2011), accounting for beta attenuation (Brennan, 2003). Cosmic-ray dose rates were calculated using the approach described in Prescott and Hutton (1994). Internal dose rate contributions for K-feldspar grains have been estimated using an assumed internal ^{4} K content of 12.5 ± 0.5% (Huntley and Baril, 1997) and ^{87}Rb content of 400 ± 100 ppm (Huntley and Hancock, 2001). The long-term water content was taken as being equivalent to the present-day water content values measured for each sample, which ranged between 4% and 14% of dry weight. An uncertainty of 20% was added to the water content to account for any potential minor variations during the past. Final dose rates are shown in **Supplementary Table S1**. Present-day secular equilibrium of the ^{238}U and ^{232} Th decay series was investigated via additional high-resolution gamma spectrometry (HRGS) measurements. Daughter-parent isotopic ratios for ^{238}U, ^{226}Ra, ^{210}Pb, ^{228}Ra and ^{228}Th are consistent with unity at either 1σ or 2σ for all three samples, indicating that the ^{238}U and ^{232}Th chains exhibit present-day secular equilibrium (see **Supplementary Table S2**).

3 RESULTS

3.1 Luminescence Results

Elevated temperature pIR-IR signals measured at 225°C (pIR-IR_{225} protocol shown in **Supplementary Table S3**) were used to date the samples in this study following the results of dose recovery tests performed using different pIR-IR measurement conditions (see **Supplementary Table S4**). Twelve aliquots containing ~160 grains of K-feldspars were measured for each sample. The natural D_e datasets of samples STL17-1 and STL17-3 exhibit low to moderate overdispersion values (19–23%) and are not significantly positively skewed according to the test of Arnold and Roberts (2011), consistent with sufficient bleaching of the dating signal prior to burial (**Supplementary Table S7**, **Supplementary Figure S7A,C**). Mean D_e values and final burial ages were calculated using the central age model (CAM; Galbraith et al., 1999). In contrast, the D_e distribution of sample STL17-2 shows significantly higher overdispersion (52 ± 12%), though it is not considered significantly positively skewed (**Supplementary Table S7** and **Supplementary Figure S7B**). These D_e characteristics may indicate insufficient bleaching of some K-feldspar grains prior to burial (or additional complications), with multi-grain averaging effects resulting in complex (non-skewed, uniform) expressions of extrinsic scatter. Statistical comparison of the CAM, the 3-parameter minimum age model (MAM-3) and the 4-parameter minimum age model (MAM-4) (Galbraith et al., 1999) results using the L_{max} test of Arnold et al. (2009) indicates that the MAM-4 provide the most suitable fit for this D_e distribution (see footnote d of **Supplementary Table S7**). Based on these results, along with insights gained from the replicate single-grain OSL measurements made on this sample (see below), we have used the MAM-4 to derive the final age for STL17-2 (**Supplementary Figure S7B**; **Supplementary Table S7**).

The single-grain OSL and TT-OSL D_e distributions of samples STL17-3 and STL17-1 are characterised by low to moderate scatter (overdispersion = 23 ± 3% and 27 ± 4%, respectively; **Supplementary Figure S8A,C**) and are not considered to be significantly positively skewed at 2σ. These homogenous D_e characteristics are consistent with the paired K-feldspar pIR-IR D_e datasets for STL17-3 and STL17-1, confirming adequate signal resetting prior to burial. The final OSL and TT-OSL ages of both samples have therefore been calculated using the CAM (**Supplementary Table S8**). The corresponding single-grain OSL dataset for sample STL17-2 (**Supplementary Figure S8B**) shows high levels of scatter (overdispersion = 60 ± 5%) and statistically significant positive skewness. This single-grain D_e dataset therefore confirms that Level 3 is affected by enhanced extrinsic dose dispersion, which may originate from: 1) insufficient resetting of residual signals for some grains during fluvial transportation, 2) localised post-depositional mixing of grains from the layer below; or 3) the inadvertent incorporation of material from the layer below during sampling (i.e., accidental cross-cutting of stratigraphic layers). It is difficult to ascertain which of these scenarios explains the enhanced D_e scatter of sample STL17-2 without further sampling. However, the MAM rather than the CAM is likely to provide a more representative burial dose estimate for Level 3 under all three scenarios. This is reinforced by the results of the L_{max} test, which suggests that the MAM-3 produces a more suitable fit for this dataset compared to the CAM or MAM-4 (see L_{max} scores and footnote d of **Supplementary Table S8**). As such, we have used the MAM-3 to derive the final single-grain OSL age for STL17-2. It is worth noting that the CAM, MAM-3 and MAM-4 age estimates for STL17-2 are statistically indistinguishable at 2σ, hence our interpretations are not strongly influenced by age model preferences in this instance.

The final luminescence ages for the three El Sotillo samples are shown in **Table 1**. The replicate K-feldspar and OSL/TT-OSL ages for each sample are in general agreement, supporting the overall suitability of the combined dataset (including our age model selections). The K-feldspar and single-grain OSL ages for Level 2 are 6.4 ± 0.5 ka and 6.7 ± 0.4 ka, respectively. Level 3 is dated to 13.9 ± 1.1 ka using K-feldspar pIR-IR and 9.5 ± 0.6 ka using single-grain OSL. The lowermost dated layer (Level 5) is significantly older, yielding consistent K-feldspar and single-grain TT-OSL ages of 303 ± 25 ka and 258 ± 17 ka, respectively. For samples STL17-1 and STL17-3, the replicate ages are consistent with each other at 1σ or 2σ. For sample STL17-2, both luminescence ages are stratigraphically consistent with surrounding ages, though they do not overlap with each other when considering their 2σ error ranges. For this sample, the single-grain OSL age of 9.5 ± 0.6 ka is preferred since it is based on measuring individual mineral grains and thus enables more useful insights into the extrinsic D_e scatter affecting this sample in the absence of multi-grain averaging effects (unlike the pIR-IR K-feldspar dataset).

TABLE 1 | Final luminescence ages obtained for the El Sotillo (excavation sector B) samples.

Sample	Level	Mineral	Luminescence Signal	Grain Fraction (µm)	Present-day Water Content (% dry Weight)	Total Dose Rate (Gy/Ka)	Age model[a]	D_e (Gy)	Age (ka)
STL17-3	2	K-feldspar	Multi-grain pIR-IR_{225}	90–125	8.1	2.62 ± 0.10	CAM	16.6 ± 1.2	6.4 ± 0.5
STL17-3	2	Quartz	Single-grain OSL	212–250	8.1	2.10 ± 0.09	CAM	13.8 ± 0.4	6.7 ± 0.4
STL17-2	3	K-feldspar	Multi-grain pIR-IR_{225}	90–125	4.1	2.36 ± 0.09	MAM-4	32.9 ± 2.1	13.9 ± 1.1
STL17-2	3	Quartz	Single-grain OSL	212–250	4.1	1.84 ± 0.08	MAM-3	17.5 ± 0.7	9.5 ± 0.6
STL17-1	5	K-feldspar	Multi-grain pIR-IR_{225}	90–125	14.3	2.19 ± 0.10	CAM	666 ± 44	303 ± 25
STL17-1	5	Quartz	Single-grain TT-OSL	90–125	14.3	1.74 ± 0.09	CAM	448 ± 17	258 ± 17

[a]*Age Models are: CAM, central age model; MAM-3, 3-parameter minimum age model; MAM-4, 4-parameter minimum age model.*

TABLE 2 | El Sotillo. Level 5 lithic industry from A and B Sectors. Totals and subtotals in bold.

	Unretouched Items	Tools	Total
0. Acquisition phase			
0.1 Cobbles with percussion marks	12	—	12
0.2 Positives of percussion	5	—	5
Acquisition subtotal	**17**	—	**17**
1. Production phase			
1.1a Flakes	1769	342	2111
1.1b Flake fragments	363		363
1.1c Backed knives on flake	—	60	60
1.2a Flakes >10 cm (macro-flakes)	8	23	31
1.2b Large flakes fragments	4		4
1.2c Backed knives on large flake	—	10	10
1.4a Cores	388	10	398
1.4b Core fragments	56	—	56
Production subtotal	**2588**	**445**	**3033**
2. Shaped tools			
2.1 Handaxes	—	52	52
2.2 Handaxe fragments	—	7	7
2.3 Cleavers on flake	—	44	44
2.4 Trihedral picks	—	7	7
2.5 Other tools on cobble	—	10	10
Shaped subtotal	—	**120**	**120**
3. Uncharacteristic products			
3.1. C*hunks*	32		32
Uncharacteristic products subtotal	**32**		**32**
Subtotal	**2637**	**565**	**3202**
Total	**3202**		

Our luminescence dating results indicate that Level 5 is a Middle Pleistocene layer (that include the lithic assemblage) deposited during 245–345 ka (weighted mean age at 2σ), which corresponds largely with marine isotope stage (MIS) 8 (Lisiecki and Raymo, 2005). The overlaying Levels 3 and 2 (devoid of archaeological record) were deposited ~9.5 ka and ~6.5 ka, respectively, during the Holocene.

3.2 Technical Study of the Acheulean Industry From Sectors A and B at El Sotillo

Our analysis of the lithic industry of El Sotillo is structured around the extended concept of *chaîne opératoire*, (Boëda et al., 1990; Inizan et al., 1999). In the exposition, we will follow the order derived from the identifiable phases in the process of elaboration and consumption of the tools (**Table 2**). We will base our study upon the technological reading of all the lithic artefacts and in the analysis of their basic physic features, such as raw material, size, and weight.

3.2.1 Petrological Features. Raw Materials Provenance

We will present the results corresponding to the study of the lithic industry recorded in sectors A and B (**Supplementary Figure S1, S3**). The series studied was obtained in the 2017 and 2018 campaigns and comes entirely from stratigraphic level 5 (**Figure 3**), particularly levels 5.1 and 5.3, gravel lags where the industry is concentrated, separated by a sterile sandy-clay deposit (level 5.2). In total, an area of 14.9 m^2 was excavated: 12.2 m^2 in sector B and 2.7 m^2 in sector A. The series comprises a total of 3202 pieces (**Table 2**), 693 from sector A and 2509 from sector B, producing an average density of c. 641 pieces per m^3 of sediment in sector A and 514 per m^3 in sector B. This data corresponds to the highest concentrations of industry recorded in Acheulean sites on the Iberian Peninsula in a similar sedimentary environment -fluvial gravel bars- (**Supplementary Table S9**).

Trench C-D (40 m^2) was opened in the 2017 campaign. From the trench, areas D and F were excavated in 2018 and 2019 (**Supplementary Figure S1**). Two levels with lithic industry were obtained (**Supplementary Figure S2**), and their ongoing study has allowed us to attribute them to the Acheulean and Mousterian, respectively. These levels are stratigraphically above the Acheulean level of the A and B sectors.

About 99% of the lithic assemblage found at El Sotillo level 5 (sectors A and B) is composed of different types of quartzite. Locally, quartzite is the most abundant raw material; it is available and easily accessible in the "Raña" or in the Quaternary terraces and colluvium. It is composed of orthoquartzite, quartzite, quartz arenites pebbles and blocks with a sandy matrix. The primary source of these rocks is the lower Ordovician formation outcropping in the adjacent hills, such as Sierra de Malagón and Sierra de Fuenluenga in the north and Sierra del Sotillo south of the site.

Moreover, there is also one specimen in quartz and one in aphanitic volcanic rock. Although quartz is not abundant in the region, it can be found in veins with decimetric to metric thickness of the Lower Ordovician series, associated with fractures in the NNE-SSO direction. The larger veins are represented in the geological maps in the western region of the Montes de Toledo, about 10 km in an SSE direction and in a straight line from El Sotillo. Also, some small quartz pebbles of between 2 and 6 cm can be found in the terraces in the vicinity of El Sotillo.

Volcanic formations of the Upper Miocene and Lower Pleistocene are known in the region, corresponding to the NW sector of the Spanish Central Volcanic Region or Campo de Calatrava. An outcrop of hydromagmatic deposits within the sedimentary Pliocene deposits and associated eruptive pipes can be found, controlled by fault systems, in the Ordovician formations of the bedrock. The closest volcanic formations to El Sotillo are eruptive cones associated with a fault located 6 km away in a straight line in the SW direction and a hydromagmatic deposit 10 km away in the W direction, in the vicinity of Porzuna.

Less than 1% of the lithic material in the excavated trenches is exogenous although regional geological mapping indicates that its provenance is likely not far away. Of this material, seven pieces are chert. Among the chert pieces, there is one scraper, and the rest are flakes or knapping products. It is particularly noteworthy that four of these chert pieces are small-sized knapping residues likely from the same support, most probably a large tool, which may have been brought to the site already configured and then re-shaped.

Current data indicates that the raw material exploited is almost entirely local, available at least within a 10 km radius of El Sotillo. However, it should be noted that there is no sign of chert within this radius. The few specimens in chert, especially the four pieces mentioned probably came from the same support and

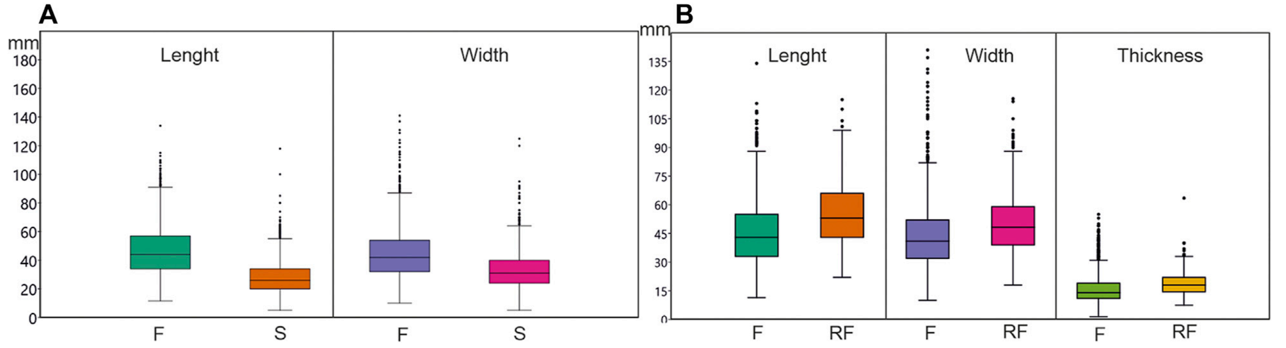

FIGURE 4 | (A). Boxplot of the typometric values of flakes and macro flakes retouched and unretouched–F- (Length, N=1732; Width, N= 1834) and scars identified in cores–S- (N = 1625). **(B)**. Boxplot of the typometric values of unretouched flakes–F- (Length, N=1385; Width, N= 1519; Thickness, N= 1776) and retouched flakes–RF- (Length, N=266; Width, N= 315; Thickness, N= 425).

indicate greater mobility in the landscape and differentiated curation and management strategies of resources.

3.2.2 Raw Material Acquisition and Production Phases

The raw material acquisition phase (**Table 2**) is only represented by 12 cobbles with traces of use as a hammerstone and five fragments produced by the use of these artefacts. All of the recognised hammerstones are quartzite pebbles, ranging from 112 to 53 mm in length and weighing 763–66 g. Half of them weigh between 344 and 399 g, two are smaller (66 and 80 g) and only one is significantly larger (763 g). These elements are perfectly proportionate for the knapping of cores and configured tools recorded on site. The reduced representation of percussion elements, especially of small pieces suitable for retouching, is explained by textural features of fluvial deposits where the availability of cobbles suitable for use as percussion tools is very high. For this reason, there is no need for repeated use of the same element, leading to pieces with low-intensity use-wear traces that are difficult to identify.

Cores and flakes are the main component of series (94.7%). Part of this assemblage (14.7%) corresponds to retouched tools, including backed knives. All phases of core and artefact reduction are represented, from fully cortical products to flakes with no cortex remains, double bulbar-faced flakes (Janus and Kombewa), and knapping and retouching flakes. There are also elements characteristic of the reduction of the flaked surfaces in the cores, such as plunging flakes, core-tablet and semi core-tablet, and flakes produced on the more organised extraction surfaces (**Supplementary Table S10**). Some flakes with Levallois morphology were identified. However, given the absence of cores from this method, we interpret that they may have come from the centripetal surfaces exploited in discoidal cores, or even from the handaxe shaping.

The overall dimensions of the flakes (**Figure 4A**) show a weak presence of elements with lengths of less than 35 mm. The most frequent values observed in the core scars are practically unrecorded in the series studied. This situation must be related to the negative influence of the sedimentary environment on the preservation of smaller pieces. Smaller values observed in the cores (**Supplementary Table S11**) are absent or under-represented in the flakes of the series.

By comparing the measurements of flakes and cores (**Supplementary Table S11**), as well as those of the large flakes with larger dimensions greater than 10 cm, belonging to the largest cores (**Supplementary Table S12**) we can observe that practically all the flakes of the series could have been produced in the cores contained in it. There are only a few large flakes with measurements larger than those of the cores studied (**Supplementary Table S12**). On the other hand, in the cores we can observe scars of smaller sizes than those of the flakes in the series studied (**Supplementary Table S11**).

Taking into account this range of flake size recorded -including support flakes from part of the cores-the balance between flakes and cores shows a proportionality of 6.1/1. Considering the 120 tools configured (**Table 2**) and, out of these, the ones made on flakes (71 pieces in total, 26 handaxes, 44 cleavers and one trihedral pic), this index drops to 4.9/1. These values are an approximation of real proportions between products and flaked supports. The indexes obtained show that not every flake produced is preserved in the excavated fluvial deposit and that the smaller ones, in particular, are missing. The direct relationship between cores and flakes is proven, and the set of flakes preserved can be accepted as representative of production in the initial and middle phases of the exploitation of the cores and of the production of the configured tools that make up the series.

A total of 398 complete cores were identified, 10 of which are retouched and 56 fragmented, most of them probably during their exploitation. Flakes are the most frequent support (54.1%), slightly more than cobbles, despite the availability of cobbles of various sizes and shapes. Among these, angular cobbles (32.1%) were chosen more frequently than globular cobbles (8.8%), and, to a lesser extent, cobbles of rectangular cross-section (5.0%) (**Supplementary Table S13**).

The technical interpretation of the cores is based on the identification of the exploitation system through the reading of the flaking sequences and the identification of hierarchical or equivalent -interchangeable- exploitation surfaces. The type of support, the intensity of exploitation and the size of the removal negatives have also been taken into account in order to establish comparisons with that of the flakes.

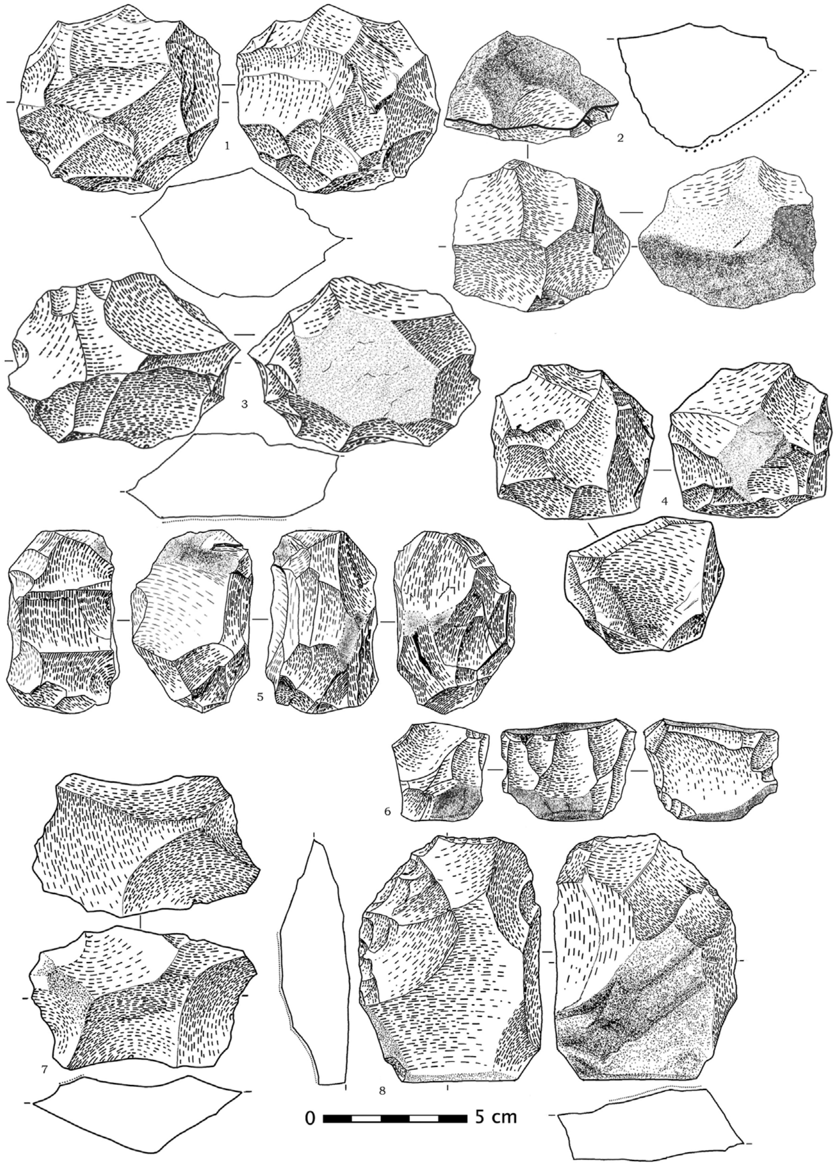

FIGURE 5 | Cores. Discoidals: bifacial (1), unifacial (2) and discoidal with differentiated striking platform (3); multipolar (4); peripheral monopolars (5, 6); bifacial on flake (7), and bifacial on flake retouched (8). All on quartzite.

Poorly organised exploitation systems (occasional, monopolar and bipolar) account for 26.1% of the knapping methods identified. Bifacial (22.5%) and discoidal (20.7%) exploitation are also frequent, and to a lesser extent peripheral monopolar (14.0%) and multipolar exploitation (8.8%) (**Figure 5**. 4). In 18 cores, the application of more than one method has been recognised (**Supplementary Table S13**).

In bifacial cores, a portion of the outline was reduced bifacially from the equatorial edge (**Figure 5**. 7–8). Among the cores with a centripetal extraction method (Mourre 2003a), those with two extraction surfaces–bifacial discoidal–are more common than those with only one. Few hierarchical specimens with defined peripheral percussion platforms have been recognised (**Figure 5**. 1–3). The peripheral monopolar group (**Figure 5**. 5–6) includes specimens with perpendicular and peripheral extractions to flat percussion surfaces cortical in some cases and formed by wide extractions in others. This exploitation system can be related to the Quina method (Bourguignon 1997), which we have recorded in African Acheulian sites from the Lower Pleistocene (Santonja et al., 2014).

Specimens developed on flakes can be recognised in all the exploitation systems (**Figure 5**. 7–8). These cores have produced flakes with double ventral faces, which have been recognised in 42 flakes in the assemblage (**Supplementary Table S10**). There are also 15 kombewa cores (**Supplementary Table S13**) in the strict sense (Tixier and Turq, 1999), which have produced single flakes, or several independent ones, taking advantage of the convexity of the ventral surface of the supporting flake.

Although rare, 10 cores retouched, after being exploited, have also been identified, forming tools comparable to those made on flakes, half of which are scrapers (**Figure 5**. 8), as well as notches, denticulates and awl. In addition, the presence of 32 core residues or chunks, which, when combined with the frequency of cores and flakes, confirms that the production process took place at the site.

3.2.3 Consumption Phase: Retouched Flakes

The identification of retouched artefacts in the El Sotillo assemblage allows us to recognise the consumption phase. These artefacts have been analysed following a technological methodology (Inizan et al., 1999: 67 and ff.). The typological terminology applied follows that established by F. Bordes (1961). They have been analysed following an analytical methodology that takes into account the location, direction and shape of the retouched side (Inizan et al., 1999: 67). We have accepted to keep the backed knives in the group, although, in the absence of traceological confirmation, they are theoretical tools, sometimes selected for use only because of their morphology.

A significant number of flakes (342 pieces, not including large flakes) displays modifications from retouching (**Supplementary Table S5**). Alongside this group, 60 configured flakes that follow the concept of backed knife (Bordes 1961) with a typical, cortical or debitage back must be considered. In total, 402 pieces represent 15.9% of the flakes under 10 cm (groups 1.1a, 1b and 1c, **Table 2**). There are 145 scrapers of very different sub-types, and they are the most common group (36.1%). Notches (25.4%) and backed knives (11.9%), with retouched backs and with cortical or *debitage* backs, are also common. The average sizes of these pieces are larger than those of unretouched flakes, but it is interesting to note the presence of tools with lengths of less than 25 mm (**Supplementary Table S11**).

Often, scrapers have single retouched edges, straight or convex -in a few cases concave- and in a lateral or transversal position. The retouching can be direct or inverse, well-defined and carried out with a hard hammer. Generally, the retouching is simple, although examples exist with semi-abrupt retouching or stepped retouching (**Figure 6**. 16). Amongst these scrapers, there are a significant number of pieces with backs, in which the cutting edge opposes a frequently cortical back, in some cases with debitage or retouching (**Figure 6**: 12, 15, 18). There are also double scrapers, sometimes with alternating retouching, and in many cases, convergent with regular and well-defined shapes (**Figure 6**. 17–19).

Most of the notches are multiple, extensive and unretouched, with two or three independent notches present on each piece (**Figure 6**. 1–2). There are fewer numbers of denticulates (**Figure 6**. 9–11) than scrapers, and although few in number, there is also a presence of more specialised tools, such as end-scrapers (**Figure 6**. 7, 8) and awls or becs (**Figure 6**. 3).

In addition to the above group, we must add the group formed by the retouched large flakes. In this group, the proportion between unretouched and more configured retouched products, 12 and 33 pieces respectively (**Table 2**), is the inverse of that observed in the previous assemblage. 73.3% of these products are retouched, suggesting that the large flakes may have been specially chosen to be transformed into tools. When comparing the size of these pieces with those of the cores (**Supplementary Table S12**) we cannot rule out the possibility of on-site production and we cannot provide arguments to support possible introductions from outside. However, the features of the dorsal face of these flakes indicate that a significant part, in particular 11 pieces (**Supplementary Table S15**), come from discoidal exploited platforms, and only in two discoidal cores does the largest dimension exceed 100 mm (102 and 114 mm, respectively). Eight of the 11 flakes mentioned measure more than 115 mm, reaching up to 188 mm, so it is not possible for them to come from the discoidal cores recognised at the site and they may have been introduced from the outside, already retouched.

The presence of 23 macro tools on flakes larger than 10 cm is another noteworthy part of the El Sotillo assemblage. In addition to 18 scrapers (Goren et al., 2008), three notches and two denticulates are also part of this group. The most frequent scrapers are convergent, with seven pieces (**Figure 7**. 5 and 6) and there are also five transversals (**Figure 7**. 1, 2 and 4), three double, two single lateral convex and one inverse (**Figure 7**. 3). Some present extensive retouching, but most have simple continuous retouching, similar to that observed in smaller specimens. This group also includes 10 backed knives, specimens with retouched backs (3), debitage backs 4) and cortical backs (3). The measurements and weights of the retouched large flakes are distributed between 114 and 188 mm for the largest dimension of complete pieces (17), and between 240 and 1180 g for the same group, with respective averages at 139.0 mm and 533.6 g. In the case of the slightly larger backed knives, the mean values are 141.9 mm and 571.1 g, with values ranging from 106 to 207 mm for the length and 344–1460 g for the weight.

3.2.4 Consumption Phase: Shaped Tools

Here, we analyse artefacts shaped on natural blank or a large flake by a specific knapping sequence, with the aim of producing a specific object (Inizan et al., 1999: 41 ff.). This set comprise handaxes, cleavers on flake and trihedral picks. In addition, we add other tools to this group, which are also made on natural blank. In total, they represent 120 pieces (**Table 2**), confirming the attribution to the Acheulean techno-complex of the studied assemblage.

In the identification of the handaxes, we start from the technological concept of bifacial shaping, according to which it is possible to divide the bifacial shaped into two phases: drafting and finishing. The first is mainly related to the bifacial volumetric proportion and the second to the bilateral symmetry (Inizan et al., 1999: 41 f.). At El Sotillo, it constitutes the largest group with 59 pieces, comprising seven fragments, one preform and 51 complete tools (**Figures 9**, **10**). Four of the fragments probably correspond to the tips of lanceolate handaxes. They correspond to finished specimens and may have been produced accidentally during use. In two of them, we can observe the intervention of an organic hammer in the finish and, in another, retouching that

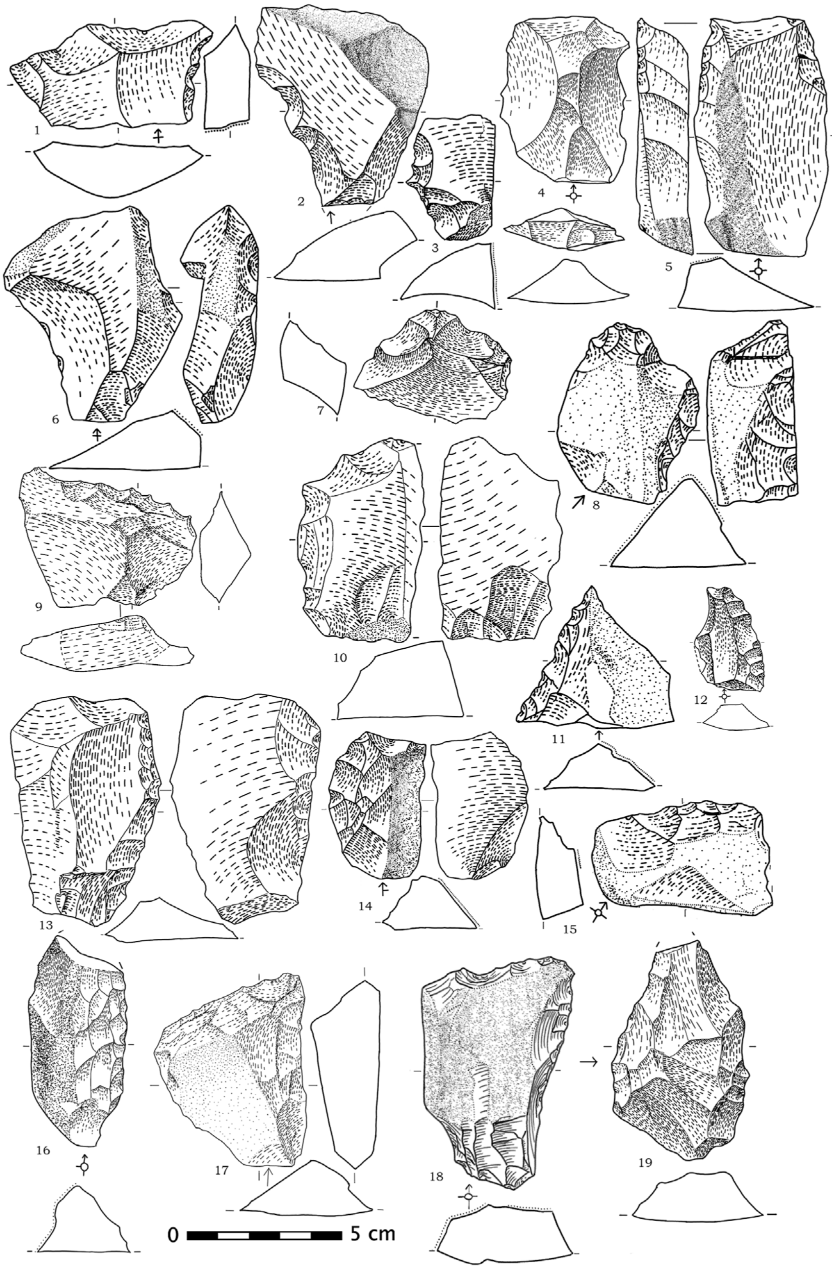

FIGURE 6 | Flake tools: double notches (1, 2); bec (3); flake with Levallois morphology (4); typical and cortical back knives (5, 6); end-scrapers (7, 8); denticulates (9, 10, 11); convex scrapers (12, 13, 14), straight scraper (15), straight scraper with stepped retouch (16) and convergent scrapers (17, 18 and 19). Chert (18) and quartzite (1-17 and 19).

defines a scrapper on one side (**Figure 10**.9). In addition, three basal fragments and one preform, a piece abandoned during the shaping process. The presence of this type of residue confirms that at least some of the bifaces were shaped on-site.

Sizes of handaxe not affected by fractures vary between 61 and 181 mm. Two groups can be distinguished, with both pointed and unpointed specimens in both groups. There are 23 complete pieces with sizes between 60 and 115 mm and another 14 specimens larger than 140 mm, with two intermediate values (**Figure 8A**). The weights show a further contrast between the two groups. In the smaller group, weight varies between 50 and 222 g, with 11 pieces below 100 g. In the larger group, the weight ranges from 437 to 980 g, with only two pieces weighing less than 500 g. The average length of the whole complete handaxes is 114.8 mm, which is not very representative of the distribution observed. Ten pieces show distal fractures probably caused by use, and in only 3 cases is retouching observed on the fracture itself (**Figure 9**. 1).

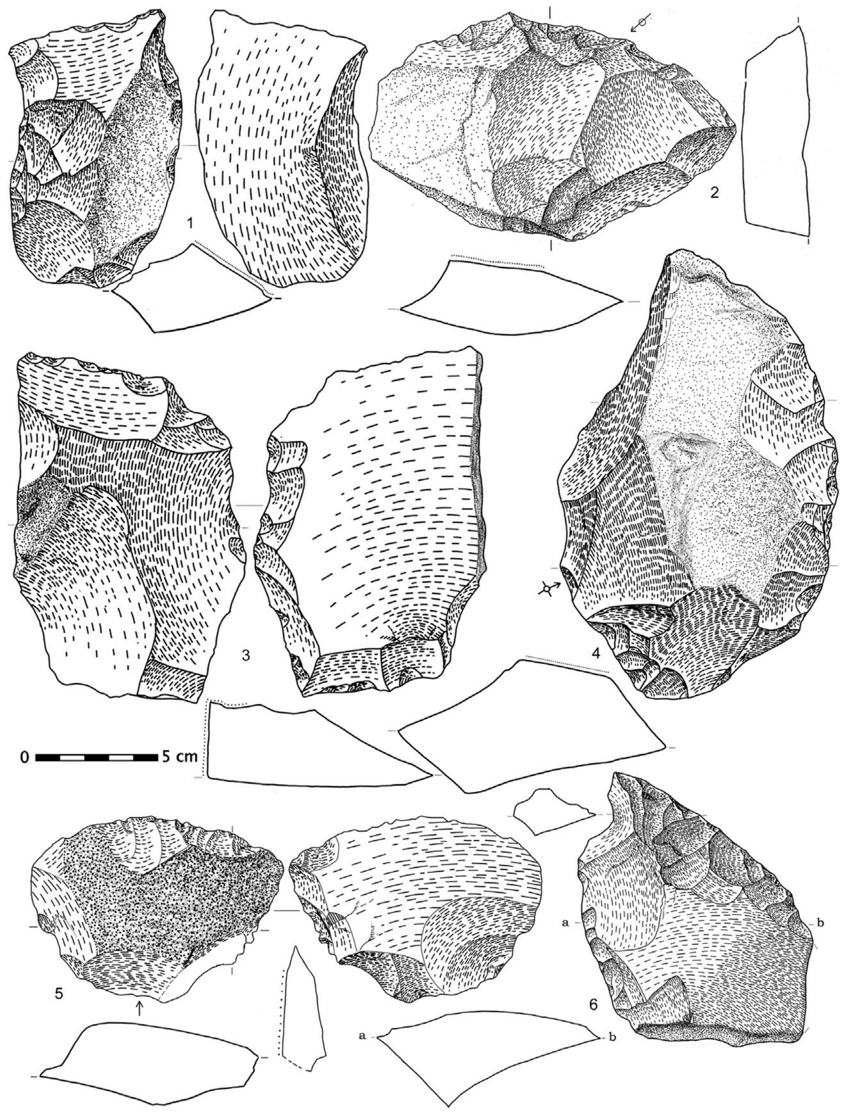

FIGURE 7 | Scrapers on large flakes: Single transversal (1, 2 and 4), inverse (3) and convergents (5 and 6, this one associated whit a notche). All on quartzite.

Most of the handaxes (80.4%) have pointed silhouettes, with a high proportion of lanceolate, amygdaloid and cordiform shapes (cf. Bordes 1961). The presence of a small subtriangular handaxe is exceptional. Non-pointed handaxes make up the remaining 19.6%, with ovate shapes being the most regular, in conjunction with a transverse cutting edge specimen and two other core-like handaxes with a less well-defined outline (**Supplementary Table S16**).

There are 20 examples of handaxes with amygdaloid silhouettes (**Figure 9**. 4–5 and 10.3–5) and six with similar but flatter silhouettes (**Figure 10**. 6–8), with width/thickness ratio higher than 2.35, which can be differentiated as cordiform (Bordes 1961). In 13 cases they have been made on flakes, with only two on flattened cobbles and another two on angular cobbles. The knapping is generally bifacial and invasive, affecting the basal area, with the intervention of an organic hammer in the final regularisation in 14 pieces. In general, silhouettes are symmetrical, with both sides convex, although among the amygdaloids there are four specimens with one straight side, one with a concave side and another with a straight cortical back on one of the sides (**Figure 10**. 5). A small transverse cutting edge is observed on three amygdaloid (**Figure 9**. 5) and on three cordiform handaxes. One of the amygdaloid has two opposing notches in the basal area (**Figure 9**. 4). Two others in this group display retouched lateral sectors, in one case using stepped retouching, forming a scrapper, and in another, a denticulate edge. In one cordiform handaxe, the final retouching creates another denticulate edge. Overall, three handaxes support-tools have been recognised (cf. Boëda et al., 1990).

The classic lanceolate handaxes are characterised by straight edges converging towards a pointed end, which is opposed to a globular base (Bordes, 1961). Those recorded at El Sotillo constitute a representative group (**Figure 9**. 1–3, eight and

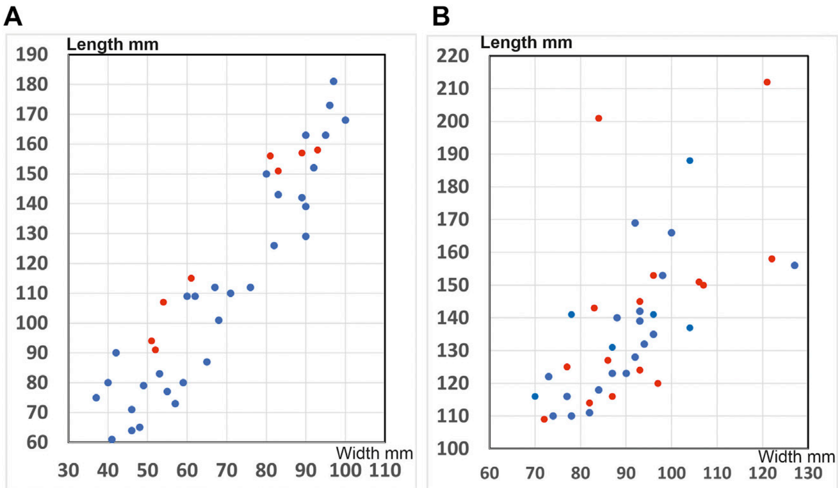

FIGURE 8 | Scatterplot of length and width measurements of the unfractured handaxes **(A)** and cleavers **(B)**. **(A)** Red dot, pointed handaxes. Blue dot, non-pointed handaxes. **(B)** Red dot, types 0 and I of cleavers. Blue dot: type II of cleavers and variants.

Figure 10. 1–2). However, some of them deviate from the general characteristics indicated, either due to their narrow straight terminal cutting edges–three specimens– (**Figure 9**. 1) or slightly dissymmetrical silhouettes with a somewhat convex side in two cases (**Figure 9**. 8). The major exception is the presence of nine lanceolate handaxes with no globular base -i.e., sharp base- (**Figure 9**. 2 and 3). As in the case of the amygdaloids and cordiform handaxes, flakes are the most common identifiable support in six specimens. Flattened cobbles as a support are recognised in two handaxes and an angular cobble in another. The bifacial shaping is generally extensive, and in five pieces any residue of its supports has been eliminated. The intervention of an organic hammer is recognisable in eleven pieces. Opposing notches close to the basal area are also observed in two lanceolates (**Figure 9**. 8), confirming that this is an intentional technical gesture, which may have the purpose of facilitating some form of hafting.

A handaxe with a flat subtriangular outline (Bordes, 1961), with asymmetrical sides, concave and convex, and a thick cortical base (**Figure 9**. 7) completes the group of pointed handaxes. This piece is not made of quartzite, but of chert, a rock that is not known in the immediate surroundings of El Sotillo, and may have already been worked when it was introduced into the site.

Handaxes with a non-pointed silhouette are not frequent and are reduced to seven ovals (**Figure 10**. 10–12) -three of them narrow ovals, *limandes*, in the terminology of Bordes, 1961-, one piece has a transversal cutting edge (**Figure 9**. 6) and two are core-like. In one of the ovals there is a small distal tip and in another a narrow bevel, also at one end. The base is sharp in three of the ovals and thicker in all of the others. As far as retouched edges are concerned, only one of the core-like edges displays two contiguous retouched notches. There are hardly any support-tool handaxes in this group. In three of the ovals, an organic hammer was involved in the finishing (**Figure 10**. 10, 11), while in the rest only lithic hammer knapping is recognisable. Flake is the most frequent support identified, in four ovals and the two core-like. In the others, only the use of a flat cobble is recognisable in the transverse edge handaxe (**Figure 9**. 6).

The presence of typical cleavers on flake (we strictly follow the concept defined in Tixier, 1956) at El Sotillo, only slightly fewer in number than the bifaces, is a key element for placing your industry in the context of the Iberian Acheulian with African roots, which also extends to southern France, the Garonne and Tarn valleys (Tavoso 1978; Mourre, 2003b; Santonja and Villa, 2006; Turq et al., 2010; Santonja et al., 2014; Rubio-Jara et al., 2016; Méndez et al., 2020; Santonja, 2020).

There is a certain balance between those shaped on cortical flake -15 of type 0 and one of type I- (**Figure 11**)- and on non-cortical flake -28 of type II, variants included (**Figure 12**)-. No specimens of Tixier type VI (on flakes with a double bulbar face) have been observed, contrasting with the frequency of flakes of this technology detected in smaller sizes. This aspect highlights that the production of Janus or Kombewa flakes at El Sotillo focused on products smaller than 10 cm, not suitable to shaping cleavers.

Type 0 pieces include five specimens with a deep bifacial knapping configuration (**Figure 11**. 3–5) relating them to Tixier's type V; however, it is possible to recognise that the supports are cortical flakes, although sometimes very much on their limit (**Figure 11**. 3). In any case, it is important to take into account this intense shaping in order to avoid automatically interpreting type 0 cleavers as poorly elaborated tools.

Eleven type 0 cleavers show practically a full configuration on both faces and even in the basal area (**Figure 11**. 1–2), which is sharp in nine examples. Eight of them were made from side-struck flakes (**Figure 11**. 1, 4), with technical measurements of length less than the width, while the rest were made from flakes obtained from the base of the tool (**Figure 11**. 2–3, 5–6). In general, the shaping is intense, with knapping affecting both sides and even the base, giving rise to rectangular silhouettes in 11 specimens. Seven of them present a thick knapped base, four are

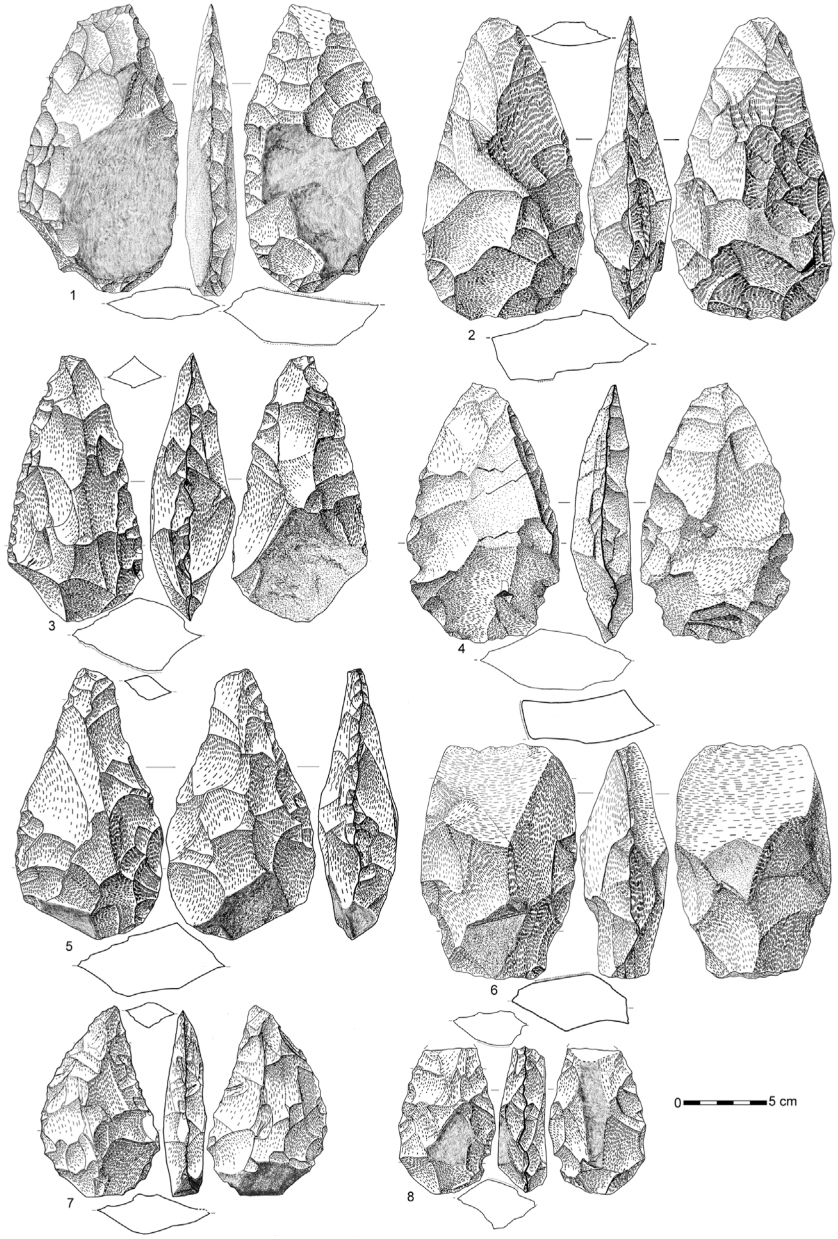

FIGURE 9 | Handaxes. Lanceolate (one to three and 8), amygdaloid (4 and 5), transverse cutting edge (6), and subtriangular (7). Quartzite (1-6 and 8) and chert (7).

V-shaped with only one case of convex sides and a somewhat ovate silhouette. This group is dominated by convex cutting edges and only four pieces with straight edges were recognised. There are no specimens with concave cutting edges, which is very difficult to obtain without retouching on a cortical flake. Their sizes are also homogeneous, with a group of six pieces with lengths between 141 and 166 mm (mean 153) and another group of six specimens between 110 and 128 mm (mean 118.8). Between them, there are three cleavers measuring 135 ± 1 mm, and above them, another one with a length of 201 mm.

Type II includes 28 pieces, on non-cortical flakes obtained from discoidal (7), bipolar 2) and monopolar 1) cores. The rest comes from unidentifiable cores. In a significant part, nine specimens, the cutting edge is defined by the intersection of the flake's ventral plane with a negative in an oblique or vertical direction. At El Sotillo there is only one specimen attributable to type I (**Figure 11**. 6). It is interesting to note that the main technical gesture that defines this type I -the presence of a negative forming the cutting edge before the extraction of the supporting cortical flake - is a resource that is also applied at this site to the configuration of cleavers of type II on non-cortical flakes (**Figure 12**. 1, 3–7, 10–12). Another variant we include in type II comprises pieces in which the cutting edge is defined by the intersection of a cortical strip with the ventral surface of the

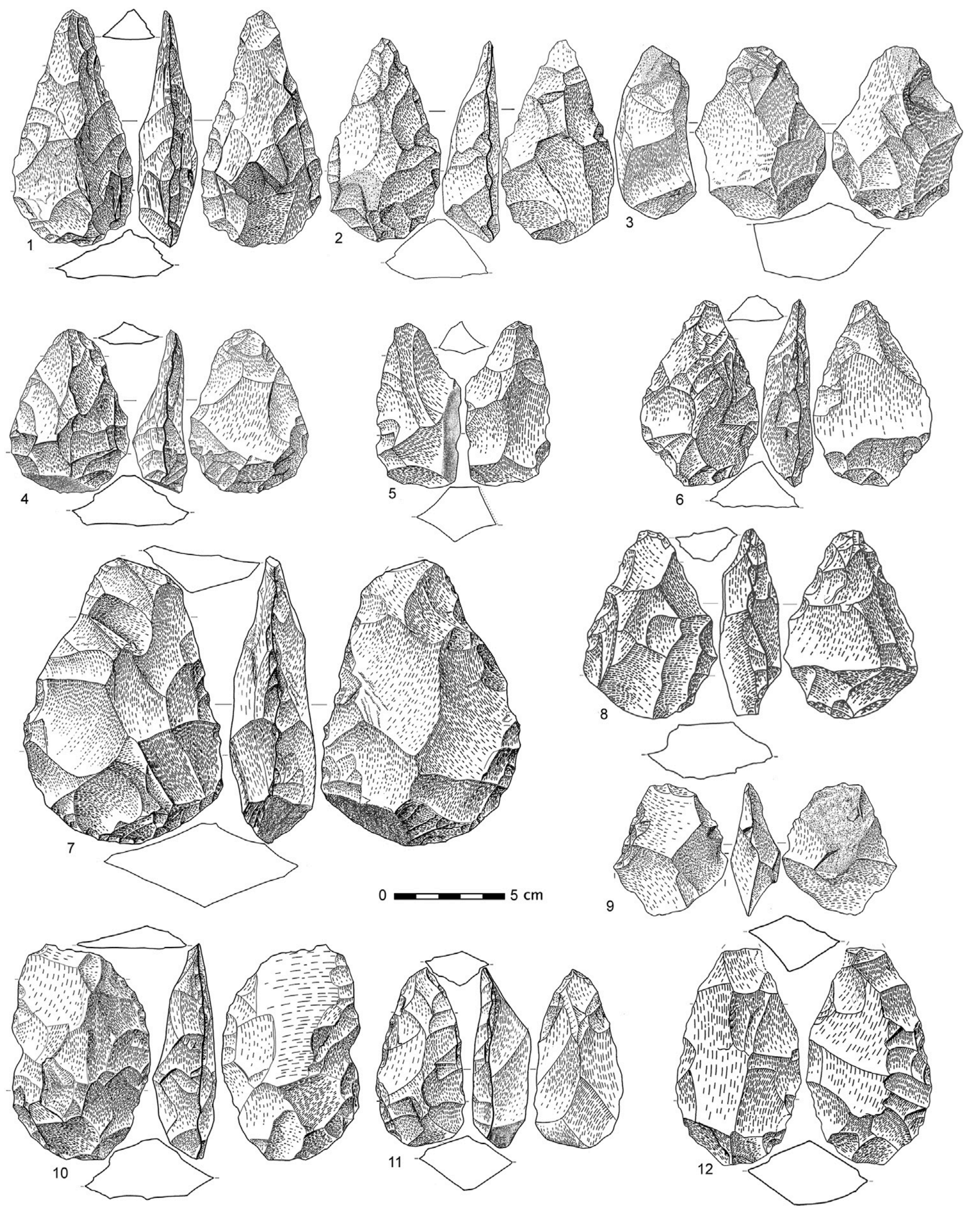

FIGURE 10 | Handaxes. Small and medium-sized lanceolate (1-2), short amygdaloid (3-4) and short amygdaloid with back (5), cordiforms (6-8), oval (10) and elongated oval (11-12). Retouched biface tip (9). All on quartzite.

flake (**Figure 12**. 8–9). These are pieces on flakes that are not entirely cortical and repeat the intentional selection of flakes with peripheral cortical strips as a support for the cleaver. Sometimes, these types of cleavers have been integrated into a new type VII (Benito del Rey, 1972-73; Mourre, 2003b).

The cleavers we include in type II show complete configurations of both sides and the base in 20 pieces (**Figure 12**. 3–5, 7). In six of them, the knapping affects one lateral side, while on the other side the area affected is limited (**Figure 12**. 1, 6), the configuration is completed by backs of various kinds, either cortical, an extensive negative or a deep distal bending of the supporting flake, a technical detail that is repeated in three cases, creating perfectly defined orthogonal laterals to the flaking plane (**Figure 12**. 12).

On two pieces, the shaping was already defined on the support flake itself on both sides; on the first, by means of the butt on one side, and on the second, by a large negative overhang almost orthogonal to the ventral plane of the flake support (**Figure 12**. 11). On the other piece, the supporting flake comes from a flattened cobble and the two sides of the cleaver are defined by cortical planes (**Figure 12**. 10). In the first of these specimens, there are two alternate opposing notches close to the base (**Figure 12**. 11) in a position similar to those observed in two bifaces (**Figure 9**. 4 and 8), as noted above.

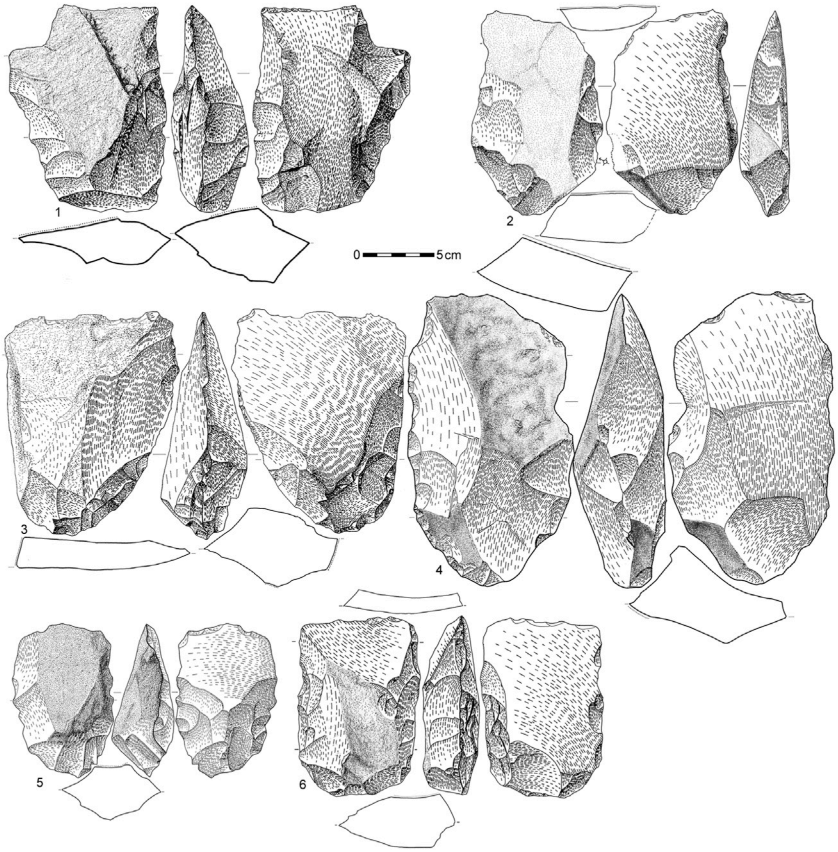

FIGURE 11 | Cleavers on flake of type 0 (1, 2), of type 0 with extensive and deep knapping (3-5) and cleaver of type I (6). All on quartzite.

The majority of the silhouettes of the type II cleavers 22) display a rectangular shape (**Figure 12**. 1–3, 7). Two of them have a slightly re-entrant side. There are five specimens with a V-shaped silhouette (**Figure 12**. 4–6, 10) and one that is oval, with two convex laterals. The cutting edges are varied, except for a fractured edge, we observed a similar number of straight (11, six of which are oblique) and convex 12) edges. In two cases the cutting edge is concave and in one case it is angled straight-straight. In almost all of them, there are macro-traces of use. The bases are thick in 14 specimens, sharp in 11 and V-shaped in three.

Six pieces have been identified as having an elongated shape and a pointed end with a triangular cross-section and an opposing massive base, knapping or cortical, which fits the concept of trihedral shaping (Inizan et al., 1995: 51) (**Figure 13**. 1–3). Most of them were made on an angled cobble with knapping on the three planes forming the pointed end. Another piece, on a flattened cobble is less characteristic from a volumetric point of view (**Figure 13**. 4), although it has a triangular section tip with knapping on the lateral planes, opposite a thick cortical base. This type of trihedral pick has been recognised in other Acheulean sites on the Iberian Peninsula (Querol and Santonja 1979: 124-141). The trihedral picks in the El Sotillo assemblage have an average length of 162 mm, with a maximum of 217 mm and a minimum of 114 mm. These values are similar to those recorded for handaxes; however, the average weight of the trihedral picks (764 g) is higher than that of the handaxes in accordance with the massive nature of these tools.

Finally, it is worth noting the presence of 10 flattened cobbles with a rectangular section, retouched to form tools similar to those found on flakes and macro flakes. Among the former, we recorded three single scrapers (**Figure 13**. 5), two of them opposite a retouched back and one convergent (Figure 16.6), a denticulate (**Figure 13**. 9) and a bec formed by the intersection of two notches (**Figure 13**. 8). The lengths of these pieces range between 40 and 90 mm, with an average of 65.7 mm. These measurements and types are similar to those observed in retouched flakes. This group is completed by another four slightly larger pieces, in the large flake range with lengths between 106 and 133 mm, with an average of 118.0 mm, comprising three macro-scrapers and a piece with a triangular silhouette, rectangular cross-section and wedge-shaped longitudinal section, with a V-shaped base and straight cutting edge, forming what was very probably an intentional pattern (**Figure 13**. 7), as it has also been recorded on two flakes.

3.3 Other Palaeolithic Sites at Porzuna

The municipality of Porzuna, covering an area of 212 km^2, is partially framed by hills with scree slopes and foothills that extend towards the E-W axis of the Malagón-Porzuna synclinorium (**Figures 1**, **2**). The Becea and Bullaque basins are a potential

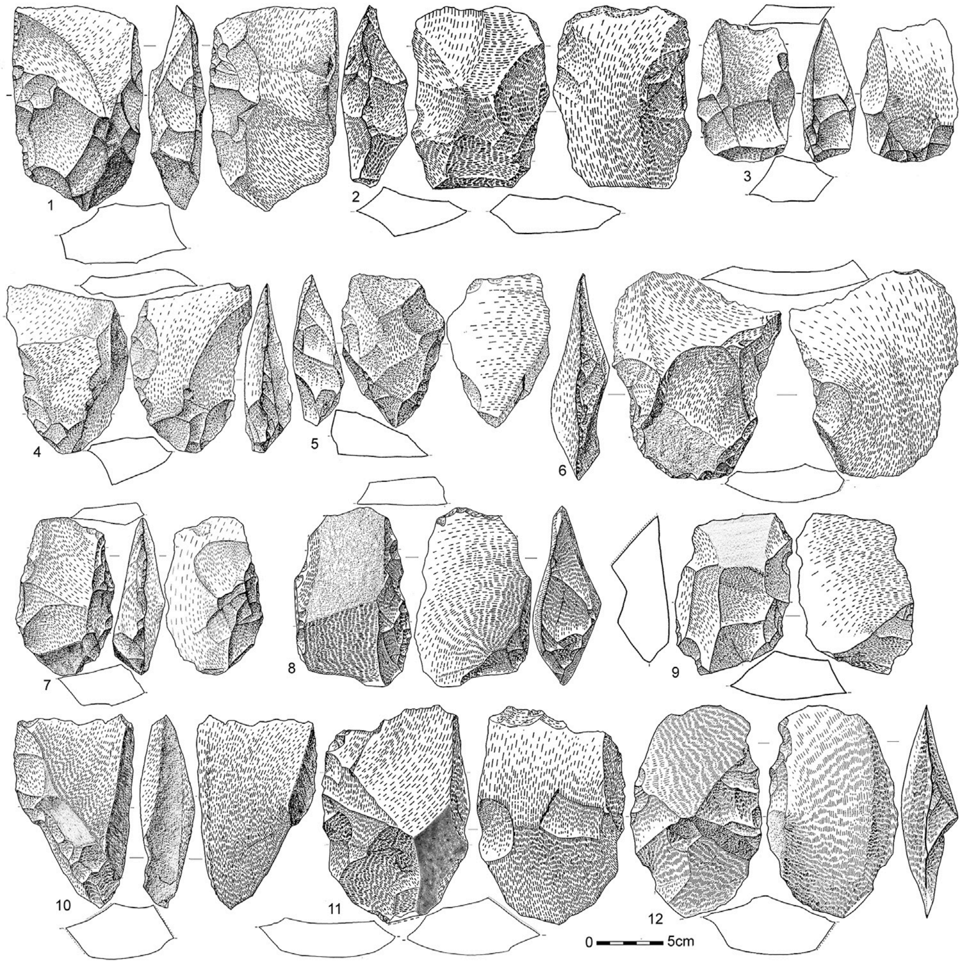

FIGURE 12 | Type II cleaver on flake (1-7), and variants with a cortical edge (8-9) and partially shaped on the core (10-12). All on quartzite.

area for the preservation of Pleistocene deposits, as are the small streams that rise on the slopes of the sierras to the north and south of the municipal district, especially the areas with springs similar to El Sotillo. To the SW are the stepped and apparently well-preserved terraces of the Bullaque River, the highest of which link up with piedmont-type formations of alluvial origin.

The N sector of Porzuna is characterised by the wide alluvial plains of the Bullaque and the foothills of El Trincheto and El Torno rivers. These are flat alluvial plains, close to the quartzite hills from which the alluvium integrated into the *Rañas* originates.

Surveys carried out have made it possible to record Palaeolithic sites in all these sectors and to carry out stratigraphic verification surveys in several of them. The localities in the south-western area, in the Las Casas del Río sector, are located in the valley of the Bullaque River, mainly associated both with this river's low terrace, at +5 m, and with alluvial fans developed on the northern slope of the immediate Sierra de Utrera. Some courses of the Bullaque River, an anastomosed fluvial course since the Pleistocene times, erode the distal positions of this fan and it is mainly in these positions where deposits have been recorded. The surveys carried out have revealed a total absence of lithic industry in the stratigraphy, while on the surface, the Acheulean industry collected in the past by amateurs was very abundant and representative.

On the lower terrace of the Bullaque River we find the classic sites of Las Casas del Río, Las Tiñosillas and Solana de los Monteros (**Supplementary Figure S9**), which were published under the general name of "Porzuna" (Vallespí et al., 1979 and 1985) and have become a reference for the peninsular Acheulean (Santonja and Pérez-González, 2002; Santonja and Villa, 2006). The areas with surficial lithic industry extend for almost 4 km along the valley floor of the Bullaque River, upstream and downstream of Las Casas del Río. The lithic industry obtained in these localities -tens of thousands of pieces partly stored in the Museum of Ciudad Real-, interpreted as representative of the Acheulean techno-complex (Arroyo and de la Torre, 2013; Arroyo et al., 2019), come strictly from surface levels after the terrace formation. Test pits opened in the terrace revealed a deposit of hydromorphic soils affecting silty-sandy muds with carbonates and hardened manganese concretions, which is 140 cm thick and completely sterile. The lithic industry that was recorded in the past comes from a coarse clastic alluvial facies fossilising the fluvial terrace.

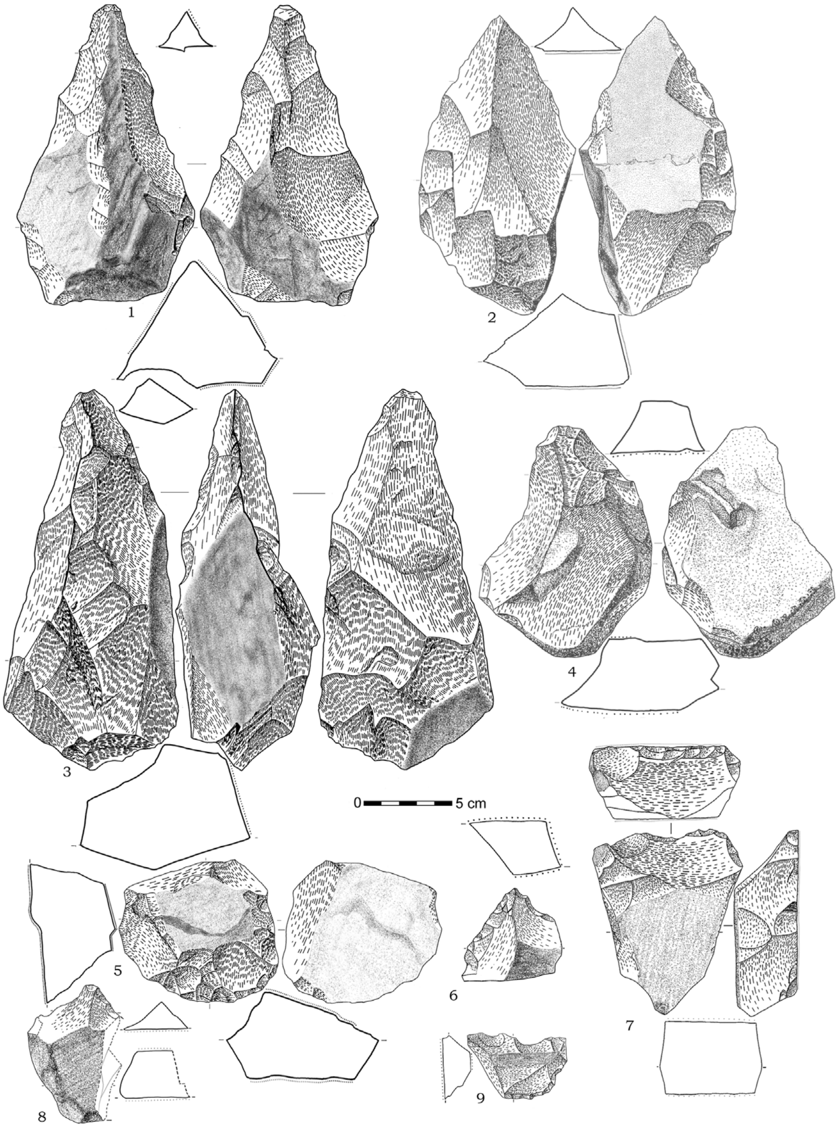

FIGURE 13 | Trihedral picks (1-4) and other pebble tools (5-9). All on quartzite.

In the south-eastern and northern sectors of the Porzuna district, we have also recorded numerous sites on alluvial fans and to a lesser extent in valley bottoms, in some cases also on river terraces, with paleolithic industry also on the surface. This situation has become a constant feature in the region for the numerous Acheulean and Middle Palaeolithic assemblages recorded.

4 DISCUSSION AND CONCLUSIONS

The known Acheulean sites on the Iberian Peninsula are almost exclusively located in Atlantic drainage basins, in fluvial formations of the Miño, Duero, Tagus, Guadiana and Guadalquivir basins (Raposo et al., 1985; Raposo et al., 1985; Cunha Ribeiro, 1999; Méndez-Quintas, 2007; Santonja and Villa 2006; Santonja and Pérez-González, 2010; Rubio-Jara et al., 2016; Panera et al., 2019; Méndez-Quintas et al., 2020). On the Cantabrian region, sites have also been reported (Arrizabalaga and Ríos, 2012), while in the Mediterranean drainage basin, only in the upper basin of the Ebro River some sites have been mentioned on terraces of this river close to Pamplona (Beguiristain, 1995). The influence of the Mediterranean climate and fluvial regime in the rest of the Mediterranean area has not favoured the preservation of sites in fluvial deposits (Santonja and Pérez-González, 2002).

Almost all known Acheulean sites on the Iberian Peninsula are located on river terraces. Most of these localities only provide lithic industry, although there are also some where the associated fauna shows outstanding features, such as Torralba and Ambrona (Sánchez-Romero et al., 2016), Valdocarros (Yravedra and

Domínguez Rodrigo, 2009; Rubio et al., 2016) or Áridos (Yravedra et al., 2010). Therefore, they are related to ancient valley bottom landscapes when they are in stratigraphic position. A pattern of repeated placement has been observed in some of the most prominent cases, such as Porto Maior and Arbo (Miño River, Pontevedra), Pinedo, Cañete Bajo and Puente Pino (Tagus River, Toledo), La Maya (Tormes River, Salamanca) and El Sartalejo (Alagón River, Cáceres) (Santonja and Villa, 2006; Méndez-Quintas et al., 2018; Méndez-Quintas et al., 2019) in areas that constitute ecotones of high trophic capacity, and now we have to add El Sotillo to the list. The availability of diversified resources in small territories, characteristic of this type of environment, may have favoured recurrent occupations by hunter-gatherer groups in the Pleistocene.

Technologically, the Acheulean assemblages recognised in the river terraces of these regions are characterised by the use of a non-standardised flake production system and retouched tools with low degree of shapes systematisation. Shaping processes dominate in the operational chains of these industries, and debitage is often oriented - as in the African Acheulean - towards obtaining large-sized flakes that are used as a support for the manufacture of handaxes and cleavers. These essential characteristics of the Iberian series are only evident in SW France, but have not been recorded in any other European region. Usually, the raw materials are of local access and the quartzite is the more common raw material. The peninsular geological conditions do not allow the extensive conservation of faunal remains in all open-air sites, although there are examples of sites with large presence of faunal remains (Santonja and Villa, 2006). The features of the peninsular and Aquitanian Acheulean, mainly the extensive use of large flakes and cleavers on flake, relate these assemblages to the African technocomplex and clearly differentiate it from that identified in other more northern regions of Europe.

Possible Acheulean assemblages have also been noted in caves with different technological features from those recognized in open-air sites. At Atapuerca (Burgos) the complete sequence of Galería (Ollé et al., 2016; García-Medrano et al., 2017) and the upper levels of Gran Dolina (Ollé et al., 2016), as well as minor references at Sima del Elefante (de Lombera-Hermida et al., 2015). Another outstanding site is Gruta da Aroeira in Portugal (Daura et al., 2017 and 2018). At Galería, the number of tools per each level is very low, especially of clearly Acheulean implements, and they may come from outside the cave. This circumstance makes it impossible to prove the occupations established inside the cave (Santonja and Pérez-González 2021). The upper levels of Gran Dolina (TD10.1 to TD10.4, from top to bottom) displays large concentrations of faunal remains and lithic tools, that correspond to successive occupations in the cave. These assemblages are interpreted as "Mode 3″ and in the case of TD10.1 as a transition between "Mode 2″ and "Mode 3″ or "Late Acheulean" (Ollé et al., 2016), despite being a level stratigraphically above those attributed to "Mode 3". The Gruta da Aroeira assemblage (comparable to TD10.1) is characterized by extensive production of flake tools, with the presence of some handaxes, but without cleavers and other large flake tools, as is also the case in TD10. From our point of view, the lithic assemblages recognized in Aroeira -where a human skull with primitive Neanderthal characteristics was also recorded (Daura et al., 2017) - and throughout TD10 may correspond to the Early Middle Palaeolithic recognised in the Iberian Peninsula from chronologies around 350 ka (Santonja et al., 2014). The few handaxes recorded in both localities could be intrusive elements in this context (Méndez-Quintas et al., 2020; Santonja and Pérez-González, 2021).

In the regions of the Guadiana River basin studied here, as well as in other immediate areas within the province of Ciudad Real, the existence of numerous Acheulean and Mousterian localities has been reported since the 1970s (Santonja 1976; Vallespí et al., 1979; Vallespí et al., 1985; Ciudad Serrano, 2000). They are almost always in a superficial position, except for some Acheulean assemblages located on +8 m and +14 m terraces of the Guadiana and Jabalón rivers (Santonja and Pérez-González 2002, and references therein). The Mousterian sites in this region have generally been recorded, both in surface and in sedimentary sequences of large-radius alluvial fans, often sourced from quartzite reliefs and occupying extensive areas. The industrial series studied comprise mainly basic production chains with cores and unretouched flakes, with a clear presence of the Levallois method (Martín Blanco et al., 1995; Jiménez et al., 1996). Although precise chronological references are lacking, the technological analysis justified the interpretation of these industries as Mousterian.

The Acheulian of the Guadiana basin has references in stratigraphic position, such as Albalá and El Martinete, on terraces of the Guadiana River at +8 m and +14 m. The assemblages obtained at these positions represent limited series with some tens of pieces coming from the existing profiles, which include handaxes and cleavers characteristic of the Iberian Acheulean technocomplex. The importance of these sites lies in the fact that allows us to place their age within the last third of the Middle Pleistocene. The largest known Acheulean industry in the region is that of the deposits of the Bullaque River at Las Casas del Río and Las Tiñosillas (Porzuna municipality), where the surveys carried out confirm that they lack a stratigraphic context.

The site of El Sotillo has an outstanding place in the Iberian Peninsula Acheulean technocomplex, within the context described above. The excavations carried out in 2017–2019 revealed a fluvial sedimentary sequence, with lithic industry in three different positions. In addition to the assemblage studied, there are two other assemblages with high densities of industry, even higher than that of the level studied here, and technological characteristics that allow them to be interpreted as Acheulean and Mousterian. Such high concentrations must be related to the poor drainage capacity of the fluvial courses in the sector, in the Becea river network, which was ineffective in displacing the excess coarse load available, including the lithic industry.

The series of level 5 of sectors A and B of the El Sotillo site come from a fluvial sedimentary environment and have experimented some disturbances, although their intensity has not been sufficient to extensively change the features of the *chaîn opératoires*. It displays a balanced and proportional relationship between flakes, cores, and other supports; and the size of the flakes is consistent with the size of the scars on the cores. However, the intensity of the sedimentary process removes the smaller size fraction, in addition to the soft abrasion on the surfaces of the tools, which prevented us from obtaining traceological results.

As seems to be the norm in the Peninsular Acheulean, no Levallois technology is observed. In addition to elementary core exploitation systems such as monopolar, bipolar, multipolar and bifacial, the most organised methods respond to discoidal and peripheral monopolar schemes. The presence at El Sotillo of well-defined flake tools, as well as that of handaxes, cleavers on flake and other shaped tools, indicates that a variety of activities were carried out in the site area. Due to natural weathering, no use-wear traces were preserved, and these activities could not be identified. The frequency of handaxes and cleavers on flake, links this industry to the Acheulean techno-complex developed on the African continent and spread throughout the Iberian Peninsula and the south of France. Particular technical skills resources have been observed in the configuration of the cleavers, such as the use of cortical backs and debitage, especially planes produced by distal bending of the flakes. The series studied, with its unique technological characteristics, is one of the largest Acheulean assemblages with a defined stratigraphic provenance currently known on the Iberian Peninsula and in Europe. In a regional context, El Sotillo is a key-site. It provides materials in stratigraphy position comparable to those surficial materials found at Porzuna, also providing a chronological reference that allows us to place this group of sites around the MIS 8.

The surveys carried out in Porzuna and in the area around El Sotillo have provided significant elements for recognising the specific landscape and environmental model in which the site is located. Fundamentally flat, open landscapes, in which the watercourses are very weakly down cutting, with endorheic areas that would maintain small lakes and even abandoned river branches in the broad plains of the anastomosed fluvial network of the main rivers, such as the Bullaque. This morpho-hydrological model also includes numerous springs at the foot of the hills. They drain from the slopes and give rise to short watercourses, many of them permanent or semi-permanent, as is the case today with the El Sotillo stream and others in the region. Similar morpho-hydrological enclaves have been located at different points at the foot of other nearby hills and in relation to the low terraces of certain river courses, although with concentrations of industry in a surficial position. This intermittent recurrence of human groups over a long period of time can only be explained by the existence of an favourable ecosystem, probably determined by elements of high trophic capacity that would make a great wealth of food resources possible, as well as an abundant and varied faunal representation.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

MS, AP-G and JB manage and coordinate the research Project; AP-G and DU for stratigraphy and geology.MD and LA for dating procedures; MS, JP, EM-Q, SR-J for technological studies; AA for raw material identification; MS, JB, JP, EM-Q, SR-J for archaeological survey.All authors wrote and edited the manuscript.

FUNDING

Financial support for this research was provided by project CEN154P20, co-financed by the ERDF (European Regional Development Fund) and the Junta de Castilla y León. MS, AP-G, JP, EM-Q, SR-J, DU and AA have written the paper within the framework of this project and Grant PGC 2018-093612-B-100 funded by MCIN/AEI/10.13039/501100011033 and, by "ERDF A way of making Europe". JB contribution is funded by Project PID2019-103987GB-C33. EMQ is funded by a Post-Doc Xunta de Galicia Grant (ED481D-2022/023). MD was supported by Australian Research Council (ARC) Future Fellowship FT200100816 and ARC Discovery Early Career Researcher Award DE160100743. The excavations carried out at El Sotillo were authorized and funded by the Junta de Castilla La Mancha in 2017 (SBPLY/17/180801/000018), 2018 (SBPLY/18/180801/000071) and 2019 (SBPLY/19/180801/000006). The surveys and test pits made in 2021 were authorised by the Junta de Castilla la Mancha and funded by Porzuna town council.

ACKNOWLEDGMENTS

We would like to express our most sincere thanks to the many people and institutions that have supported our work, with special mention to Porzuna Town Council and the Museum of Ciudad Real, as well as to all the colleagues, students and volunteer collaborators who have participated. We would like to express our gratitude to Raquel Rojas, who was in charge of the consolidation and cleaning of the archaeological remains from the excavation at El Sotillo and author of the lithic drawings that appear in these pages. All authors thank the editors of special issue, especially Marie-Hélène Moncel, for inviting them to participate. Also, we thank the reviewers for their constructive comments and suggestions, which helped to improve this paper.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2022.912007/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers | Frontiers in Earth Science

ORIGINAL RESEARCH
published: 11 July 2022
doi: 10.3389/feart.2022.882110

Were Hominins Specifically Adapted to North-Western European Territories Between 700 and 600 ka? New Insight Into the Acheulean Site of Moulin Quignon (France, Somme Valley)

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OPEN ACCESS

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Specialty section:
This article was submitted to Paleontology,
a section of the journal
Frontiers in Earth Science

Received: 07 April 2022
Accepted: 13 June 2022
Published: 11 July 2022

Citation:
Moncel M-H, Antoine P, Herisson D, Locht J-L, Hurel A and Bahain J-J (2022) Were Hominins Specifically Adapted to North-Western European Territories Between 700 and 600 ka? New Insight Into the Acheulean Site of Moulin Quignon (France, Somme Valley).
Front. Earth Sci. 10:882110.
doi: 10.3389/feart.2022.882110

Current data seem to suggest that the earliest hominins only occupied the Northwest of Europe during favourable climatic periods, and left the area when the climate was too cold and dry, in the same way as Neandertal and even *Homo sapiens*. However, several sites in England and the North of France indicate that the earliest hominins, possibly *Homo antecessor* and/or *Homo heidelbergensis*, could adapt to cool environments and open grasslands without the use of fire. Recent discoveries of Acheulean lithic assemblages in early glacial fluvial deposits at Moulin Quignon in the Somme Valley in the Northwest of France reveal new knowledge on the earliest occupations in north-western territories and indicate hominins' capacity to live above the c. 45th N. under a cold climate. The site shows evidence of occupations at the beginning of MIS 16 at around 650–670 ka. These findings bring to the forefront the possible ability, flexibility and resilience of Acheulean hominins at around 700 ka to extend to northern territories during transitional climatic periods (interglacial/glacial events), even if the climate was not fully favourable. Recent fieldwork has changed our interpretation of the timing and characteristics of the earliest Acheulean techno-complexes in Western Europe over a large geographical area, from Northwest Europe to the Mediterranean coast. In Western Europe, the earliest evidence, Moulin Quignon, is now dated to a narrow timeframe, between 700–650 ka, and is the northernmost evidence of biface production. This latter is earlier than British Acheulean records. Based on new findings at Moulin Quignon, we explore whether Acheulean traditions and associated new technological abilities could have facilitated the dispersal of hominins in Western Europe over large territories, regardless of climatic conditions. Changes in behavioural flexibility, and not only phenotypic changes in *Homo* groups, have to be investigated. Here, we examine the behavioural and technological abilities of hominins in north-western Europe in light of the available environmental data and compare them to those in southern areas between 700 and 600 ka. This event occurred at the end of the "Middle Pleistocene Transition" (MPT), a period marked by cyclical climate changes and vegetation and faunal turnovers (less competition with big carnivores). The extension of the grassland habitat into higher latitudes could have led to the opening and/or closing of migration corridors in these regions, probably favouring hominin expansion depending on tolerance to climate variability.

Keywords: Acheulean, behaviours, Northwest France, environmental conditions, hominin adaptation

INTRODUCTION

Current data seem to suggest that the earliest hominins occupied the Northwest of Europe during favourable and temperate climatic periods and left the area when the climate was too cold and dry (Ashton and Davis, 2021; Moncel et al., 2021a), as in some areas of the South of Europe from the Early Middle Pleistocene onwards (Blain et al., 2021) and the Northwest of Europe for Neandertal (Hublin and Roebroeks, 2009; Locht et al., 2019). There is rare evidence of arid climatic contexts, such as for the sites of Orce (Altolaguirre et al., 2021).

Above the c. 45th N., some sites in France and the Southern England attest to climatic conditions conducive to hominin presence (**Figure 1**). They include Pont-de-Lavaud in the centre of France, dated to 1.055 ± 0.055 Ma, with a forested environment (Marquer et al., 2011; Despriée et al., 2018). If we consider the earliest evidence of occupations in Germany, hominins would also have been present during interglacial periods (Fielder et al., 2019). However, the British sites of Happisburgh 3 (Marine Isotopic Stage (MIS) 21, 866–814 ka, or MIS 25, 970–936 ka) and Pakefield (MIS 19 or MIS 17, about 750–680 ka) show that the climate was rather continental and cool for occupations dated between MIS 25 to 17 (Parfitt et al., 2005; Parfitt et al., 2010; Farjon et al., 2020). At la Noira, in the center of France, Acheulean groups were present at the end of MIS 17 and the beginning of MIS 16 and disappeared from the area when the climate was too cold (Despriée et al., 2011; Moncel et al., 2020a). These different sites, with or without biface production, indicate the capacity of the earliest hominins, possibly *Homo antecessor* and *Homo heidelbergensis*, to adapt to more or less open environments without the use of fire (Hosfield and Cole, 2018). Evidence of the use of fire is not clearly documented before MIS 11, either in the Northwest or the South of Europe (i.e., sites of Barnham, Beeches Pit, La Celle and Terra Amata, Limondin-Lozouet et al., 2010; Schreve et al., 2002; Rosell and Blasco, 2019).

Recent discoveries of Acheulean lithic assemblages at Moulin Quignon in the Somme Valley in the Northwest of France (**Figure 1**) transform our knowledge of the earliest occupations in north-western territories and suggest that hominins were capable of surviving under a cold climate. The site provides evidence of occupations at the beginning of MIS 16 at 650–670 ka (Antoine et al., 2019). Before that, the Acheulean was recorded in the Somme Valley at the beginning of MIS 12 at Cagny-La-Garenne (Antoine et al., 2007) and some artefacts found at the site of Rue du Manège dated to ca. 550 ka, at the

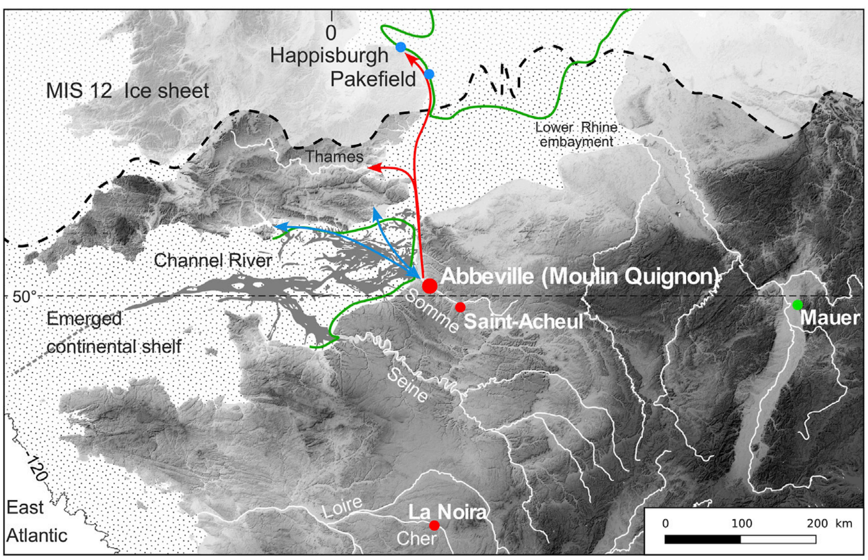

FIGURE 1 | Location of Abbeville-Moulin Quignon and of some Mode 1 sites in Southern England (blue dots), Acheulian sites (red dots), and of the Homo heidelbergensis type-site (Mauer) in Europe. Marine Isotopic Stage 12 ice sheet is located according to Ehlers et al., 2011, Cromerian shoreline (green) to Hijma et al., 2012. Arrows: possible communication routes during interglacial (red), and glacial (blue) periods (modified from Antoine et al., 2019).

MIS 14 - MIS 13 transition, indicated that the Somme Valley was occupied earlier than anticipated (Lamotte and Tuffreau, 2001; Antoine et al., 2003; Antoine et al., 2016).

Finally, recent discoveries at Abbeville following the re-discovery of the former Moulin Quignon site in the sands and gravels of the High terrace of the Somme River indicate that hominins occupied Moulin Quignon above the c. 45th N under a cold climate at the beginning of MIS 16, ca 670–650 ka ago. These findings point to the ability, flexibility and resilience of Acheulean hominins around 700 ka to extend to northern territories.

Current Data on the Early Acheulean

Recent fieldwork and the revision of lithic collections over the past decade have renewed our interpretation of the timing and characteristics of the earliest Acheulean techno-complexes in Western Europe over a large geographical area, extending from Northwest Europe to the Mediterranean coast (i.e., Moncel et al., 2015; ; Schreve et al., 2015; Voinchet et al., 2015; Abruzzese et al., 2016; Ollé et al., 2013; Ollé et al., 2016; Moncel and Ashton, 2018). Core-and-flake or Mode 1 assemblages are recorded as early as 1.4 Ma, particularly in Southern Europe, attesting to sporadic occupations mainly under warm and humid conditions, mostly during glacial/interglacial transition phases (Arzarello et al., 2006; Blain et al., 2021). Biface shaping appears in Western Europe between 1 Ma and 600 ka, associated with some innovations in core technologies in some sites and the production of large flakes (Ashton et al., 2011; Moncel et al., 2013; Vallverdú et al., 2014; Voinchet et al., 2015; Moncel et al., 2021b). These innovations also take place in assemblages without bifaces suggesting various activities or traditions into the Lower Paleolithic and Mode 2. This is considerably later than in East Africa, the Levant and India (between 1.75 and 1.5–1.2 Ma) (Bar-Yosef and Goren-Inbar, 1993; Goren-Inbar et al., 2018; Lepre et al., 2011; Pappu et al., 2011; Beyene et al., 2013).

The earliest evidence of Acheulean complexes (lithic series with biface production) in Europe is found in southern Europe and comes from the site of Barranc de la Boella, Spain with some crudely made Large Cutting Tools (LCTs) dated to 1 Ma–900 ka (Mosquera et al., 2015). The site of Bois-Riquet has also yielded some bifacial tools dated to around 800 ka (Bourguignon et al., 2016). These discoveries, and some other localized cases (see details in Moncel et al., 2016), indicate the early arrival of this technology or local attempts at bifacial manufacture under more diversified climatic conditions (Vallverdú et al., 2014; Mosquera et al., 2015; Bourguignon et al., 2016). The sites of Cueva Negra and Solana del Zamborino seem considerably younger than initially anticipated, and cannot be considered today as early evidence of LCTs (Scott and Gibert, 2009; Jiménez-Arenas et al., 2011; Álvarez-Posada et al., 2017). In Western Europe, the earliest evidence of elaborate bifacial shaping with completely-shaped bifaces is now dated to a narrow timeframe, between 700–650 ka. For this key period, the three major sites are located under diverse latitudes: 1) the Italian site of Notarchirico in the south (Piperno ed., 1999; Lefèvre et al., 2010; Pereira et al., 2015; Moncel et al., 2019), recently dated by $^{40}Ar/^{39}Ar$ between 695.2 ± 6.2 ka and 614 ± 12, 2) the French site of la Noira, in the centre of France, where the lower level (stratum a1) is dated by ESR to more than 665 ± 55 ka (Despriée et al., 2011; Shen et al., 2012; Moncel et al., 2013, Moncel et al., 2015; Moncel et al., 2020a; Despriée et al., 2017b; Despriée et al., 2017c) and 3) the French sites of Moulin Quignon in the Somme Valley dated to 672 ± 54 ka (Antoine et al., 2019). Moulin Quignon is the northernmost site with biface production, and is earlier than the Acheulean British records dated by ESR and ESR/U-series to MIS 15/14 or MIS 13 for microfauna (Candy et al., 2015; Voinchet et al., 2015; Antoine et al., 2019; Lewis et al., 2021). Three hypotheses are currently advanced for the origin of these new behaviours in Western Europe, which led to the settlement of larger territories, the *in situ* evolution or an introduction by new groups or an influx of new ideas that soon reached a large part of Western Europe (i.e., Moncel et al., 2013; Martínez et al., 2014; Moncel et al., 2015; Mosquera et al., 2018; Méndez-Quintas et al., 2018; Moncel et al., 2018a; Moncel et al., 2018b). In sum, studies either describe a chronological and behavioural shift at 700 ka or gradual evolutionary trends with arrivals of new populations or at least new ideas, in relation to *Homo heidelbergensis* or other unknown hominins (McPherron, 2006; Stringer, 2011; Stringer, 2012; Mounier et al., 2009; Wagner et al., 2010; Dennell et al., 2011; Martinón-Torrès et al., 2007; Martinón-Torres et al., 2011; Sharon et al., 2011; MacDonald et al., 2012; Bermúdez de Castro et al., 2013; Bermúdez de Castro et al., 2013; Moncel et al., 2018a; Moncel et al., 2018b, Moncel et al., 2020b). The scarcity of archaeological sites over such a long period either points to poor preservation due to taphonomic processes or short-lived dispersal events with phases of depopulation and recolonization of the continent by small groups of pioneers.

The new findings at Moulin Quignon (Antoine et al., 2019) tend to suggest that Acheulean traditions (Mode 2) and new technological abilities could have helped the dispersal of hominins in Western Europe over larger territories, regardless of climatic conditions. Changes in behavioural plasticity and not only phenotypic changes in *Homo heidelbergensis* groups (or other hominins) have to be explored. We investigate the behavioural and technological abilities of hominins living in North-western Europe and compare them to those from southern areas between 900 and 700–650 ka, when the earliest evidence of biface shaping emerges in Europe; associated sometimes with innovations in core technologies. Moulin Quignon site is not only an emblematic site, rooted in the history of prehistoric sciences, but also a site where occupations point to hominin adaptions to northern territories, to harsher environmental conditions and climates, without the use of fire. The site also suggests the enhanced flexibility of *Homo heidelbergensis* compared to *Homo antecessor*.

This event occurred at the end of the Middle Pleistocene Transition (MPT), a period marked by cyclical climate changes and vegetation and faunal turnovers (less competition with big carnivores). It could have led to the successive depopulation or extinction of small groups of hominins in Western Europe (North and South), and to subsequent recolonization, before and between the MIS 16 and 12 cold events (Guthrie, 1984; Turner, 1992; Belmaker, 2009; Dennell et al., 2011; Muttoni et al., 2015; Cuenca-Bescos et al., 2011; Manzi et al., 2011;

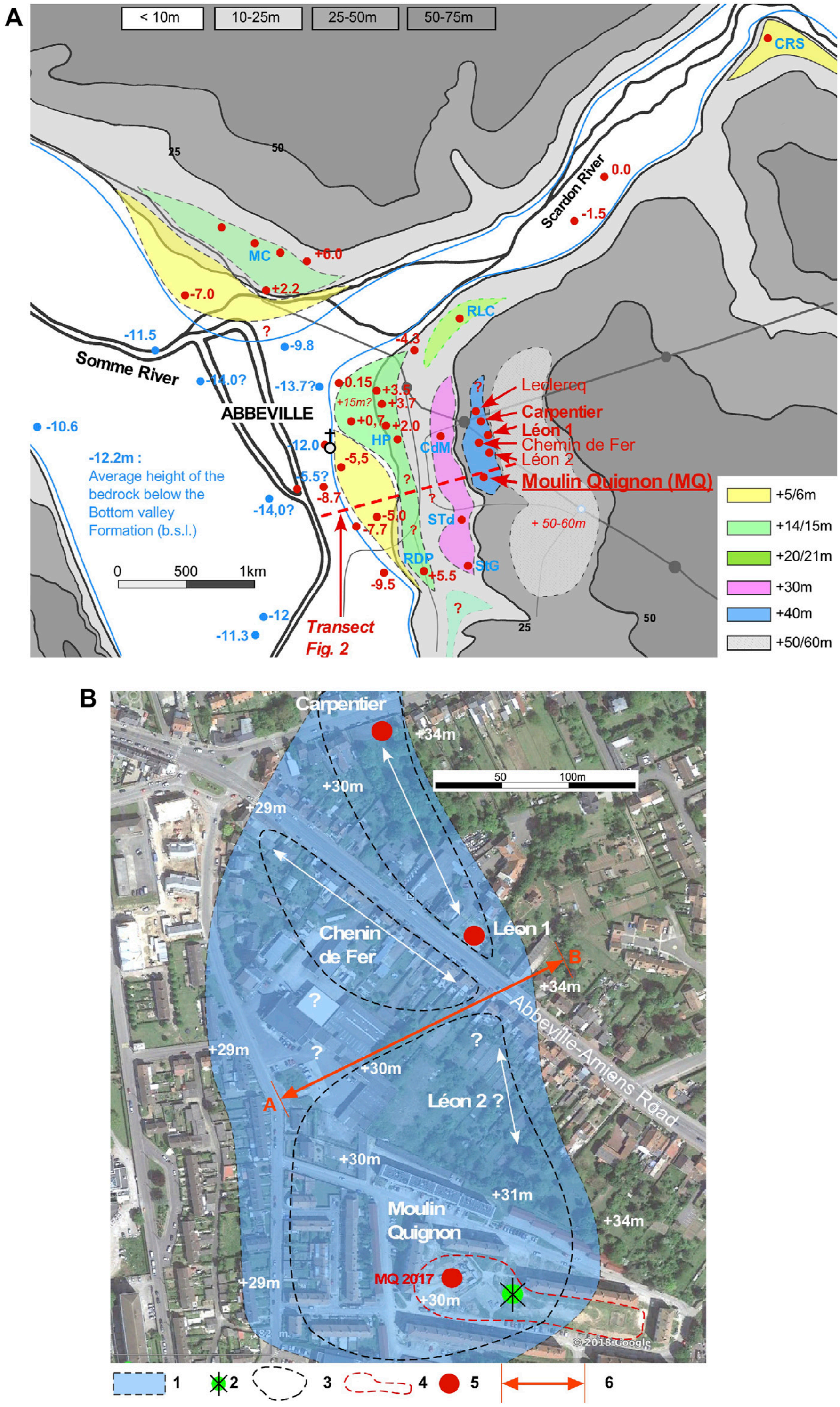

FIGURE 2 | (A) Location of the Moulin Quignon, Carpentier and Leon sites on a map of the Quaternary alluvial formations of the Abbeville area according to (Antoine et al., 2016 modified). Transect of figure 3: red dotted line. Other sites: MT-CB: Mautort-Cambron, RdP: Rue de Paris, Std: Abbeville-Stade, CdM: Abbeville Champ de Mars, HP: Abbeville Hôpital, MC: Abbeville-Menchecourt, RLC: Abbeville-Rue du Lieutenant Caron, CRS: Caours. **(B)** Detailed map of the Carpentier Alluvial Formation (+40 m) between Carpentier and Moulin Quignon, with location of all the sites mentioned in this study according to Antoine et al., 2019. 1) Reconstructed extension of Alluvial Formation VII: (Carpentier Formation, + 40 m). 2) Location of the Moulin Quignon windmill at the end of the 19th Century. 3) Attempted reconstruction of the contour of the quarries at the end of the 19th Century. 4) Area explored during the test-pit campaign in 2016 (17 test-pits) 5) Location of the recently described sequences (2012–2017). 6) **(A,B)**: Transect of **Figure 3**.

Rodriguez et al., 2011; Abbate and Sagri, 2012; MacDonald et al., 2012; Garcia et al., 2013; Carrión et al., 2011; Palombo, 2014; Palombo, 2017; Chauhan et al., 2017). The MPT is also considered to have been conducive to the extension of grasslands to higher latitudes, thereby opening and/or closing migration corridors in these regions. This change in vegetation probably favoured hominin expansion according to tolerance to climate variability, and faunal turnovers (Guthrie, 1984; Turner, 1992; Almogi-Labin, 2011; Bar-Yosef and Belmaker, 2011; Cuenca-Bescos et al., 2011; Leroyer et al., 2011; Rodríguez et al., 2011; Abbate and Sagri, 2012; Martínez et al., 2014). As indicated by sites earlier than 1 Ma, hominin occupations would only have been possible at the transition from glacial to interglacial periods during the Early Pleistocene. However, the lack of records for cold periods may also be due to taphonomic constraints and not only to the absence of occupations.

The Site of Moulin Quignon at Abbeville, Somme

History of Research

The Moulin Quignon site in the suburbs of Abbeville was discovered by Boucher de Perthes during the XIXth century. This sand and gravel quarry is located in the High Terrace on the right bank of the Somme River close to its confluence with the little Scardon River (**Figure 2**). The site yielded fossil bones of large mammals and flint "axes," but it quickly became a subject of controversy with the exhumation in 1863 of an "ante-diluvian" human mandible, found in a stratigraphic context analogous to the aforementioned 'axes' (Abbeville, 1866; Boucher de Perthes, 1847; Quatrefages, 1863a; Quatrefages, 1863b; Boucher de Perthes, 1864a; Boucher de Perthes, 1864b; Milne, 1864). (see **Supplementary Material** for details).

The gradual disappearance of quarries and urbanization in the second half of the nineteenth century in Abbeville made it even more difficult to correlate Moulin Quignon with other sequences from the Carpentier and Léon sites and arbitrary comparisons were sometimes advanced (D'Ault du Mesnil, 1889; D'Ault du Mesnil, 1896; Commont, 1909). (Breuil, 1939; Breuil et al., 1939; Hurel et al., 2016a; Hurel et al., 2016b).

The collections of Abbeville Moulin Quignon were thus forgotten for almost 150 years. Research resumed in 2012 as part of a programme dedicated to the earliest settlements and to the Acheulean, in particular in the Somme valley (Hurel, 2014; Antoine et al., 2016; Moncel et al., 2016).

The geological context of the discoveries was re-examined through the testimonies left by Boucher de Perthes, then by the geologists and archaeologists who subsequently worked on the fossil alluvium from the Somme to Abbeville (Bahain et al., 2016). This critical approach was supplemented by new studies and in particular by the results of work carried out at Carrière Carpentier, as well as by a process of mapping alluvial formations in the Abbeville sector (Antoine et al., 2015; Antoine et al., 2016) (**Figures 2A,B**). The main results confirmed the fluvial nature of the archaeological layers of Moulin Quignon, which are embedded in sands and gravels of the high terrace of the Somme (Antoine et al., 2019). The terrace lies on an incision step in the chalk bedrock located about 40 m above the maximum incision of the Somme valley in Abbeville. The dating carried out at Moulin Quignon using ESR-quartz from fluvial quartz grains provides an age ranging between 709 ± 55 ka and 650 ± 37 ka to the glacial fluvial deposits. The study of the malacofauna collected at the Carrière Carpentier, as well as the mammal fauna collected since the end of the nineteenth century in the Marne Blanche, place these alluvial deposits in an interglacial during the second half of the Cromerian (Cr. III), or to marine isotopic stage (MIS) 15 (Voinchet et al., 2015; Antoine et al., 2016; Bahain et al., 2016) ESR-quartz ages and ESR-U/Th on mammal teeth attributes an age of 584 ± 48 ka to these interglacial fluvial deposits of the Marne Blanche. This is perfectly in line with the position of the Carpentier quarry fluvial formation in the Somme terrace system (Antoine et al., 2007; Antoine et al., 2016) (**Figure 2**).

In addition to geological data, archaeological material (bone remains, lithic tools) from the old quarries of Moulin Quignon, deposited by Boucher de Perthes at the Museum National d'Histoire Naturelle, has been re-examined, in particular the carefully annotated bifaces. Their stratigraphic location is sometimes indicated by labels written by the hand of Boucher de Perthes. However, we cannot distinguish the pieces found by Boucher de Perthes from those brought by workers and given to Boucher de Perthes. Some could come from other sites. The revision of this material provided the first proof of the authenticity of the site, even though it is still impossible to specify the stratigraphic position of these pieces (Moncel et al., 2016). The few malacofaunal remains collected by Boucher de Perthes at Moulin Quignon, and curated in the collections of the MNHN, include Cromerian species confirming such antiquity (Bahain et al., 2016).

New Discoveries at Abbeville Moulin Quignon

Abbeville Moulin Quignon in the Context of the Somme River Quaternary Terrace System

During glacial periods, the palaeo-Somme valley was one of the main tributaries of the Channel River, flowing into the Atlantic, and was a likely major route for human migrations between continental Europe and southern England (Ehlers et al., 2011) (**Figure 1**). The Somme River exhibits a stepped Quaternary fluvial terrace system incised into Upper Cretaceous chalk and composed of 10 stepped alluvial formations spread between +5/6 m and +55 m above the maximal incision of the present-day valley in the Cretaceous chalk bedrock (Antoine et al., 2007) (**Figure 2A**). The relative height of the contact between the successive alluvial sequences and their respective bedrock steps can be used to securely associate archaeological layers such as Moulin Quignon with the Somme River system. In addition, in the Somme valley, each alluvial formation corresponds to the morpho-sedimentary glacial-interglacial cycle.

The terrace series can be summarized by the following phases (**Figures 2A,B–4**):

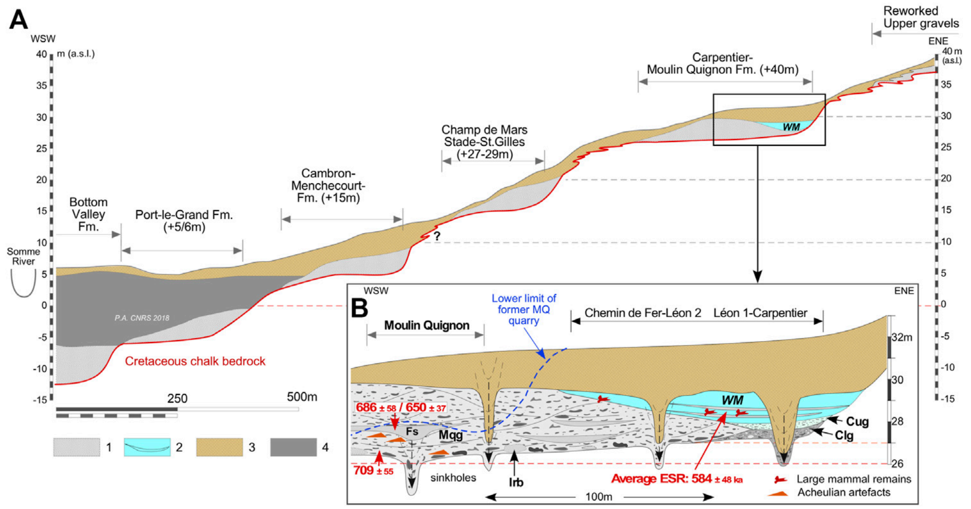

FIGURE 3 | Cross-section of the terrace system of the right bank of the Somme River at Abbeville (see **Figure 2B**). **(A)** General profile. **(B)** Detailed stratigraphic relations between Moulin Quignon and Carpentier sites on the +40 m alluvial formation and ESR-quartz dating results (according to Antoine et al., 2019). 1) Periglacial fluvial gravels, sands and sandy silts (main unit of the various terrace bodies). 2) Carpentier Marne blanche/White marl (WM) complex: interglacial calcareous silts and sandy silts with oncolith sand layers and large mammal remains (Cromerian III/MIS 15). 3) Undifferentiated slope deposits: reworked gravels and palaeosols. 4) Fluvial organic silts, peat and estuarine sands (Holocene infilling). WM: White marl. Cug: Carpentier Upper gravels: well-sorted medium flint gravels with calcareous sandy matrix, interstratified calcareous silt lenses and large mammal remains. Clg: Carpentier Lower Gravels: poorly sorted and heterometric flint gravels including numerous unrolled flint nodules and chalk blocks packed in a calcareous sandy matrix. Mqg: Non-calcareous, coarse, poorly stratified sandy gravels with iron and manganese oxide coatings at the base. Irb: large rounded blocks of reworked Tertiary sandstone (ice-rafted). Fs: Lens of laminated non-calcareous fluvial sands.

(1) Early glacial: heterogeneous coarse sediments made up of slightly reworked large chalk blocks and flint nodules embedded in a calcareous sandy matrix, including some thin lenses of fluvial calcareous silts (slope deposits slightly reworked by fluvial processes). These deposits (between 3 and 4 m thick) are only preserved in the outcrops located very close to the former slope of the valley, as in the Cagny-La Garenne or Carpentier quarry sequences. Overall, they are attributed to continental temperate conditions.
(2) Full glacial: thick body of well-sorted flint gravels including a few sand lenses (braided river system) forming the main sedimentary body of the sequence (3–4 m in thickness). The base of this unit frequently exhibits large Tertiary sandstone blocks reworked by periglacial processes from the slopes to the alluvial plain (very cold conditions, open landscape and periglacial environment, full glacial).
(3) Late glacial to early interglacial: calcareous sandy silts, more or less laminated (0.5–1.5 m thick), characterised by temperate faunas (molluscs, mammals) at the top. This unit, covering the alluvial sequence, is frequently overlain by thin organic grey marshy soil horizons (≈0.1 m).
(4) Interglacial optimum: in a few sequences, calcareous tufa beds (0.5–3.5 m thick), characterised by fully temperate bio-indicators, and especially mollusc assemblages, record the interglacial optimum, as in Caours for MIS 5e, Saint-Acheul for MIS 11, or Abbeville Carpentier for MIS15).

New fieldwork was recently conducted at the Carpentier, Léon and Moulin Quignon quarries, all located on the same +40 m alluvial formation of the Somme system (Antoine et al., 2016; Antoine et al., 2016). The stratigraphic sequence of the Carpentier quarry (average altimetry of the top of the sequence +31 m a.s.l.) is used as a reference to describe the whole sequence of this alluvial formation. It consists of a succession of fluvial gravels covered by whitish fluvial calcareous sandy silts with calcareous nodules ("Marnes Blanches" = White Marl) (Antoine et al., 2016). The fluvial succession is then covered by a slope sequence composed of hillwashed sands and thick clayey soliflucted gravel beds locally trapped in deep sinkholes. During the new fieldwork performed from 2010 to 2014 at this site, no unquestionable artefacts were discovered in the White Marl or in the underlying gravel layer, in keeping with Victor Commont's assertions, while several faunal remains were recovered in the White Marl. Moreover, no clear evidence of human intervention can be shown on the bones although the long bones systematically show helicoidal fractures generally thought to be typical of human intervention (marrow extraction) (Antoine et al., 2016). The rare potentially flaked flints were considered to be geofacts due to post-depositional effects (shocks and pressure flaking between the largest flint blocks during deposition). Two Acheulean bifaces were discovered at the base of the slope deposits directly overlying the fluvial sequence, i.e., at the same stratigraphic location as the pieces recovered by Commont, (1909). Similar types of oval-shaped bifaces were even described and related to the "Acheulean" pieces found in the gravels of the Fréville Formation in Amiens (Commont, 1909) and at the Moulin Quignon site in Abbeville (Aufrère, 1937, Aufrère, 1950; Breuil, 1939). Based on our observations and analyses, the artefacts of

FIGURE 4 | (A) Moulin Quignon 2017: stratigraphic sequence exposed during the excavation (height: 4 m) (according to Antoine et al., 2019). From the top below the reworked sandy gravels from the former Moulin Quignon quarry: Sa-br: Brown-red compact clayey sands preserved in deep dissolution sinkholes. Grs-br: brownish to reddish sandy heterometric clayey rounded gravels with small (reworked) tertiary pebbles. Fs: Yellow fine to medium laminated sands with thick (2–5 cm) red to orange oxidized bands. At its base, in places this unit shows a layer of laminated greyish clayey silts with thin oxidized orange (Fe) and black (FeMn) bands. Grs-j: Heterometric rounded sandy flint gravels with abundant yellow sandy matrix and irregular reddish to orange oxidation (Fe) bands and with (reworked) tertiary pebbles (1–4 cm). Gr-n: Strongly heterometric rounded flint gravels, without any matrix, (mainly 2–4 cm but including irregular elongated nodules up to 30 cm) and scattered (reworked) tertiary pebbles (1–4 cm). This facies is characterized by strong weathering indicated by the occurrence of brownish to blackish Fe-Mn coatings on all the flint nodules and pebbles. All the units described above are free of $CaCO_3$ due to dissolution and weathering processes that affected the whole sequence after its deposition by the river. Chalk: weathered (soft) Upper Cretaceous chalk bedrock including numerous irregular large elongated flint nodules (20–40 cm in length). **(B)** Photo of the fieldworks (P. Antoine 2017).

Boucher de Perthes are most likely coeval with the end of MIS 15 or with an early stage of MIS 14, between 550 and 500 ka (Antoine et al., 2016).

Rediscovery, Dating and Rehabilitation of the Moulin Quignon Palaeolithic Site

In this context, new investigations were undertaken in 2016–2017 at Moulin Quignon (50°06′18″N/1°50′89″E, **Figures 3**, **4**), as a result of the redevelopment of the suburb of Abbeville, leading to the rediscovery of this emblematic Palaeolithic site 170 years later (Antoine et al., 2019). In 2016, seventeen 4-to-5-m-deep test pits were excavated, resulting in the discovery of undisturbed fluvial gravels and sands, well preserved below thick layers of reworked sandy gravels (from the former quarry) and modern dump deposits. The average bedrock altitude measured at Moulin Quignon (26.5 m a.s.l.) in test pits and in the archaeological excavation is very close to the altitudes obtained for the Léon 1 and Carpentier quarries, located 200 and 400 m northwards respectively (relative height: 39–40 m). This approach demonstrates that the three alluvial remnants are located on the same bedrock step and correspond to the same alluvial formation.

The relative elevation of this Moulin Quignon alluvial formation above the altitude of the maximum incision of the chalk below the present-day valley (+40 m) correlates it with Alluvial Formation VII of the Somme system (Antoine et al., 2007).

In addition, we compiled all the available stratigraphic information for this alluvial formation from the area located between Carpentier Quarry and Moulin Quignon, taking into account our recent observations at Carpentier, Léon 1 and Moulin Quignon quarries between 2012 and 2017, as well as the former data published by D'Ault-du-Mesnil, Commont and Breuil (D'Ault du Mesnil, 1889; D'Ault du Mesnil, 1896; Breuil, 1939).

This approach was completed by a new test pit campaign during spring 2019 over an abandoned area further to the north (140–180 m) of the Moulin Quignon 2017 excavation, closer to Carpentier Quarry (**Figures 3**, **4**). During this extensive survey (17 test pits on 2,600 m^2), *in situ* remnants of fluvial gravels and sands were discovered (thickness about 1 m), overlying the same chalk bedrock step as in Carpentier Quarry and Moulin Quignon 2017.

These results strongly support the direct stratigraphic correlation between the fluvial sequences from Moulin Quignon and Carpentier Quarry, despite their distance.

The facies and stratigraphic succession observed in the new Moulin Quignon excavation are very similar to descriptions published in the nineteenth century by Boucher de Perthes and Prestwich, in terms of overall thickness of the sequences and sedimentary facies. Boucher de Perthes described a sequence composed of gravel beds and sand layers, with a thickness of about 4.5 m. This is perfectly compatible with the difference between the average altitude of the bedrock step measured at the base of the sands and gravels during the new excavations and test pits (26.5 m) and that of the surface of the topsoil (30.5–31 m). Moreover, at the very base of the fluvial sequence, we also found only at Moulin Quignon a 0.4–0.5 m-thick layer of gravels strongly coloured by iron and manganese oxides, which was formerly described by Boucher de Perthes

("Couche noire") and Prestwich (the Black band) in the same stratigraphic position, and in which we also discovered Palaeolithic artefacts.

The stratigraphic synthesis shows that the Carpentier interglacial deposit, the "White marl," extends to the south towards the area corresponding to the Chemin de Fer and Léon 2 quarries located at less than 100 m from the area explored at Moulin Quignon in 2016–2017 and that they overlie the coarse gravels and sands from the Moulin Quignon Formation.

The interglacial calcareous facies of the "White marl" is thus only preserved in sequences located in the external part of the alluvial formation. This configuration results from the occurrence of a lateral channel close to the right bank of the Palaeo-Somme valley, whereas interglacial deposits are not preserved towards the central part of the former river valley, showing a markedly thicker lower gravel unit (3–3.5 m), like in the Moulin Quignon area. Thus, combining the new observations and former data, we can demonstrate:

Given the stratigraphic information exposed above, the geochronological data from the deposits of the Carpentier quarry, and especially the ESR and ESR/U-series dates from the interglacial deposits of the White marl, can be used to reliably infer the age of the Moulin Quignon findings. Besides, three samples of sandy sediments were extracted during the 2017 archaeological excavation from the main stratigraphic units and *in situ* gamma-ray measurements were performed in each sampling hole. The results obtained for the three samples from Moulin Quignon, using the aluminium (Al) and lithium titanium (Ti-Li) centres of quartz, are consistent with each other (overlapping of uncertainty domains at 2 σ). An average age of 672 ± 54 ka was obtained for the whole fluvial sands and gravels formation of Moulin Quignon, confirming the antiquity of the site.

Although the average age of the Moulin Quignon fluvial deposits corresponds to the early phases of MIS 16 (Glacial b of the Cromerian Complex), and thus to clearly cold and markedly different conditions compared to the "Marne Blanche" deposits, no accurate palaeoenvironmental reconstruction can be attempted due to the absence of bio-indicators in the Moulin Quignon gravel formation (fully decalcified deposits).

The interpretation that the Moulin Quignon gravels and sands were deposited in a periglacial environment is based on the occurrence of some very large rounded Tertiary sandstone blocks (up to 0.5–0.8 m in length), at the base and in the fluvial gravels, reworked during episodes of periglacial mudflows from the slopes of the valley towards the alluvial plain. Indeed, in the alluvial formations of the Somme River, as in numerous rivers of Northwest Europe, these large ice-rafted blocks are described within or at the very base of Quaternary alluvial formations. The reworking of these sometime huge rounded blocks (>1 ton) from the slopes to the alluvial plains, and their subsequent transport by fluvial systems, imply that major episodes of solifluction occurred on the slopes and that extremely strong river dynamics transported large ice-rafted blocks and heavy loads of coarse and poorly sorted material (flint nodules and chalk blocks) during spring break-ups and floods.

These processes characterise full glacial conditions and are typical of braided river systems in Quaternary periglacial and present-day northern tundra environments. The deposition of the Moulin Quignon sequence during periglacial conditions is also shown (**Figures 3**, **4**) by 1) the occurrence of well-sorted flint gravel layers including a main stratified sand lens deposited in a shallow channel structure (at least 5–6 m wide) typical of braided river systems (Gr-n, Grs-j, Grs-br and Fs), 2) a very low proportion of sandy matrix as well as iron oxide and manganese coatings on the gravels (Sa-br), that are both typical of the basal units of the fluvial sequences of the other Somme terraces and, 3) the occurrence of numerous large and poorly rolled flint blocks (20–40 cm in length at the base of Gr-n), as generally found at the base of the gravel bars and islands in braided river systems (lag deposits).

Finer facies (grey silty sands, yellow laminated sands) observed in Moulin Quignon sections that could have reflected different climatic conditions, but no bio-indicators, are preserved due to post-depositional weathering processes. The thin layers of clayey-silty sands occurring at the base of the main sandy lens have been tested for pollen without success. These fine-grained sediments were probably deposited in the same braided river environment in an abandoned shallow channel between gravel bars at the end of a flood episode.

The homogeneous character of the physical characteristics (abrasion and patina) of the archaeological pieces from Moulin Quignon excludes reworking from an older terrace formation and no traces of occupation have ever been described in the older alluvial sequences of the Somme system despite more than 150 years of intensive research.

The archaeological excavation showed that the artefacts are not regularly distributed in the fluvial deposit but are rather localized in spatially discrete concentrations separated by archaeologically sterile zones.

The Acheulean artefacts discovered at Moulin Quignon thus probably represent human occupations during a cold period, located in the former alluvial plain of the Somme River on a gravel bar close to the right bank of the valley, at the margins of the valley. In this position the site was regularly flooded during spring floods and the flint artefacts were probably displaced over short distances (a few metres), before being buried in the sandy-gravelly material.

However, it is highly likely that human occupations from this period only correspond to short incursions of human groups during the summer season. Taking into account the wide dating error bars, it is also possible that the Moulin Quignon human occupation took place during a short interstadial period (≤1–2 ka) characterised by a milder climate (especially during summer season), as is the case for example for Upper Palaeolithic hunters during the Last glacial period in the area (Renancourt: Paris et al., 2016; Moine et al., 2021), or for the Acheulean occupation at Cagny-la-Garenne during the Early MIS 12 glacial period (Tuffreau and Lamotte, 2010; Lamotte and Tuffreau, 2016).

At that time, Acheulean "pioneers" probably followed the tracks made by the Somme valley and river banks along a straightforward trajectory. In this context, the occurrence of a confluence between the Somme and the Scardon River valleys, as is the case in Moulin Quignon, was a particularly good marker in the landscape. This configuration is also auspicious for large mammals, and was particularly attractive for the first Acheulean "pioneers" in the Somme Valley.

MATERIALS AND METHODS

Materials

Lithic Collections of Boucher-de-Perthes

The lithic material attributed to Moulin Quignon is abundant in museum collections; at the Musée de l'Homme and the Institut de Paléontologie Humaine (Paris), or in other French museums, despite partial destruction during the two world wars. However, for most of the pieces, no precise geographic or stratigraphic location is indicated. These series are undoubtedly from surface collections and not from archaeological excavations or quarries.

In 1860, Jacques Boucher de Perthes gave the Museum National d'Histoire Naturelle Paris a sample of the archaeological material that he collected in Abbeville and its region, consisting of several hundred pieces (Hurel, 2014). The collection of these pieces began in 1840 and the last entry in the inventory is in 1859. There is no doubt about the authenticity of the pieces that make up this corpus (with some very rare exceptions). Twenty-two of them bear various indications and are recorded in the inventory. There are, in particular, bifaces from Moulin Quignon with indications written by the hand of Boucher de Perthes between 1845 and 1863.

Our goal was to identify the pieces with clear stratigraphic attributions handwritten on labels stuck directly on the piece or on the box. These annotations have been systematically checked in the inventory.

To date, only fourteen pieces of often very patinated flint can be attributed to a layer or a "depth" in the sequence of Moulin Quignon (3, 4 and 5 m deep). According to the inscriptions, which indicate a clear stratigraphic attribution, these lithic pieces were discovered by workers in the presence of Quatrefages or collected by Boucher de Perthes himself. The two Quatrefages bifaces, extracted in April 1863 from the same layer as the "mandible", are now curated with the collection donated by Boucher de Perthes in 1860, in the reserves of the Musée de l'Homme (Nos. 2977 and 2978).

In addition, there are two bifaces (Nos. 2157-31 and 2837/27) without a precise stratigraphic position, but inventoried as coming from the sequence. They are described separately.

Finally, two other pieces (Nos. 2155-29 and 1931-27), a small ball in flint and a gelifract (discovered in 1866), with no stratigraphic position but inventoried, were considered as natural and eliminated from the study.

Our study focused above all on the technological characteristics of the lithic pieces.

Lithic Corpus From the New Excavations (2016–2019)

A total of 254 flakes, 15 cores, 5 bifaces and 4 shaped tools were discovered *in situ* at the base of the deposits in several stratigraphic groups (Gr-n, Grs-j and Grs-j) during the recent test pits (2016–2019) and excavation (2017) (Antoine et al., 2019) (**Table 1**). The material is made on flint collected from the local Middle Coniacian C4b (flint with green cortex), from secondary flint reworked in the Tertiary formations or from the Pleistocene gravels. Only eight pieces show traces of crushing and 19 are clearly flake-tools. The vast majority are fresh. The geological features of the sequence and the taphonomy of the artefacts indicate that they were moved little by natural processes (≤1 m). As there are no significant differences between the sub-layers, the corpus is studied as a whole.

Methods

The technological analysis of the lithic corpus was performed using the "chaîne opératoire" (i.e., Boëda et al., 1990; Geneste, 1991; Texier and Roche, 1995; Baena et al., 2018), in order to understand the production systems and technical objectives through the analysis and description of each object. The characteristics of LCTs were analysed by general morphology, raw material and blank (if recognizable), size, number and characteristics of removals, symmetry (bifacial and bilateral), processing sequence for the general volume and the tip, presence of cortical residue and retouch. Core technologies are identified on cores and flakes by studying the reduction processes: size of cores and end-products, type of cores (discoid, unifacial, bifacial, orthogonal and polyhedral), organization of removals on cores and flakes, extension of cortex, platform and retouch. The analysis of the retouched items focused on broad categories of tools (scrapers, denticulates and notches): size, location, extension, type and continuity of retouch, and final tool morphology.

Correlations with the current environmental and archaeological data in South and Northwest Europe are made through direct studies of material from recent research and literature.

RESULTS: TECHNOLOGICAL STRATEGIES AT THE SITE OF MOULIN QUIGNON IN NORTHWEST EUROPE

Revision of the Artefacts Found by Boucher de Perthes (Musée de l'Homme Nineteenth Century Collection)

A small series has been identified in the Boucher de Perthes collection with clear data on the origin of the finds and above all their stratigraphic depth written in Boucher de Perthes' handwriting (**Figure 5**). The material from known stratigraphic locations is mainly composed of bifaces from depths of 3, 4 and 5 m, some of which were collected near the human mandible.

TABLE 1 | Lithic corpus by layer (from the youngest to the earliest) at Moulin Quignon (fieldworks 2016–2019)—in number.

	Fs	Grs-j	Gr-n/Grs-j	Gr-sr	Gr-n	Gr-n base	Grs-br (disturbed)	Disturbed	Total
Bifaces		1	3		1	1			5
Shaped tools		1	3						4
Cores		8	4	2	1				15
Products of debitage	5	84	110	10	21	12	2	10	254

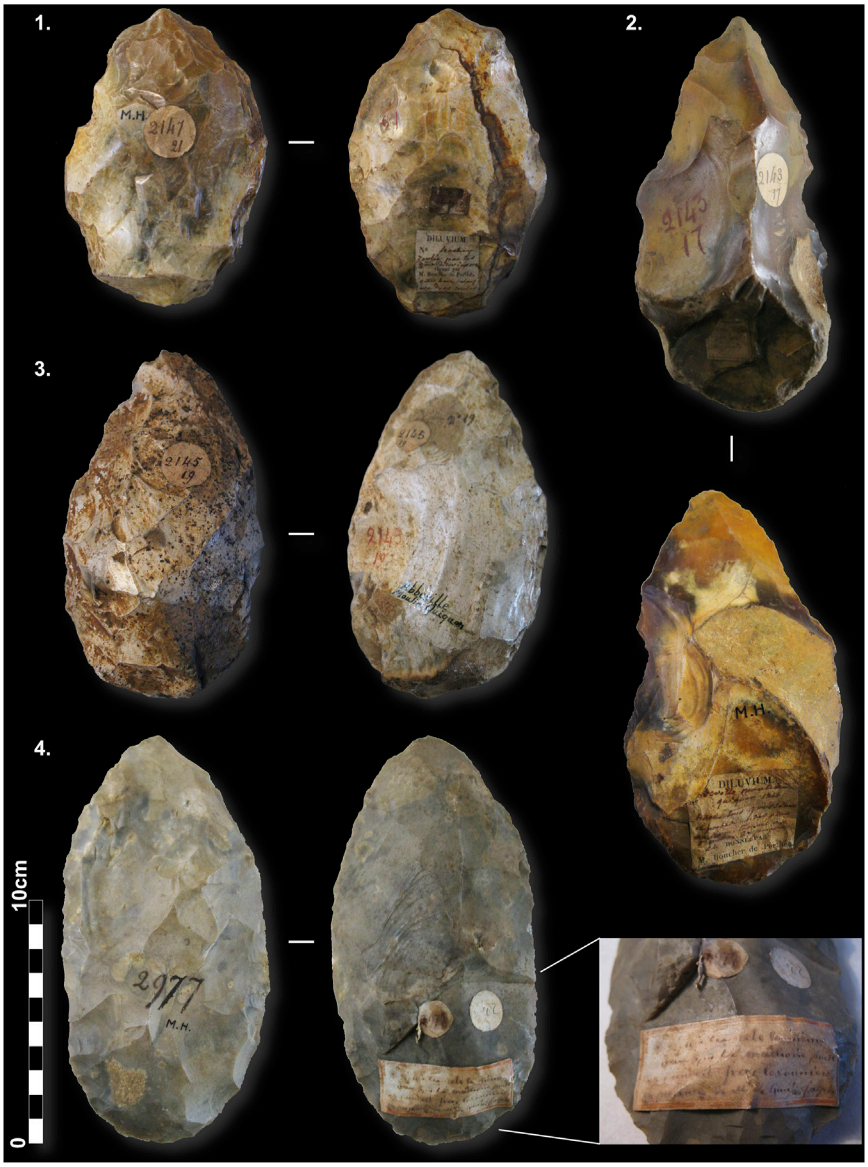

FIGURE 5 | Handaxes coming from J. Boucher de Perthes's collections of the XIXth century exploration of Moulin Quignon quarry, preserved in Musée de l'Homme in Paris. 1–3: handaxes potentially discovered in Gr-n or Grs-j layers, due to the features of the patina and the presence of well-developped ferro-manganic veneers. 4: handaxe probably introduces by workers in the stratigraphy of Moulin Quignon, next to the famous mandible as mentionned in the XIXth century label. The technical proprieties and the patina do not fit with the recently excavated artefacts in Moulin Quignon. Photos: Marie-Hélène Moncel, Rachel Orlaic. CAD: David Hérisson.

TABLE 2 | Lithic corpus by layer (from the youngest to the earliest) and technical types of flakes at Moulin Quignon (fieldworks 2016–2019) - in number.

	Fs	Grs-j	Gr-n/Grs-j	Gr-rs	Gr-n	Gr-n base	Grs-br (remanié)	Remanié	Total
indet. flakes	1	1			1			1	4
First cortical flakes		3	10	1	1	2			17
Flakes with bilateral cortical backs			1						1
Flakes with a lateral cortical back	2	8	16		2	2		2	32
Flakes with distal-lateral cortical backs		1	2						3
Flakes with a distal back					1				1
Flakes with a distal cortical back		2	4		1	1		1	9
Flakes of biface		1		1					2
Flakes of biface?	1	2	1		1				5
Flakes with a cortical butt-back			3			3			6
Flakes with cortex		37	38	3	4	2	2	3	89
Backed flakes with cortical patches		1	5						6
Flakes without cortex		25	22	4	5	1		2	60
Backed flakes without cortex			6		3				9
Kombewa flakes		1	1						2
Fragments of flakes		1		1	1				3
Fragments of elongated flakes						1			1
Elongated flakes (blades)	1		1		1			1	4
Total	5	84	110	10	21	12	2	10	254

TABLE 3 | Technical types of flakes and organization of removals at Moulin Quignon (fieldworks 2016–2019) –when readable- in number.

	Bipolar	Centripetal	Crossed	Transversal	Unipolar	Unipolar convergent
Flakes with bilateral cortical backs			1			
Flakes with a lateral cortical back		2	11	1	14	1
Flakes with distal-lateral cortical backs		1			2	
Flakes with a distal back		1				
Flakes with a distal cortical back					8	1
Flakes of biface			1			
Flakes of biface?		1			1	3
Flakes with cortex	2	6	9	1	57	3
Backed flakes with cortical patches	1		2		3	
Flakes without cortex	2	7	11		22	9
Backed flakes without cortex		3	4		2	
Flakes with a cortical butt-back			2		3	
Cortical flakes		1		2	3	
Fragments of flakes		1			1	
Elongated flakes	1				1	
Total	6	23	41	4	118	17

Two bifaces were collected at a depth of 3 m. The biface extremity is not diagnostic (No. 2149-23). The complete biface (No. 2150-25) measures 10 cm, and is shaped by a few removals, with irregular edges, despite unifacial retouch on one edge.

Five flint pieces come from a depth of 4 m, including two flakes measuring around 10 cm. Two of the three bifaces were found in direct association with the human mandible discovered in 1863. The first one (No. 2977) is a cordiform elongated biface, largely shaped face by face. The section is plano-convex and the form is symmetrical. The second one (No. 2978) is also symmetrical, cordiform and elongated, shaped by several series of invasive removals. Bifacial secondary retouch covers the periphery of the tool. Earth residues are still visible on both sides, trapped in the retouch. A third biface, without a number, is an asymmetrical oval bifacial piece on poor-quality flint. The section is trihedral and it is made by abrupt or flat removals. One side is thinned by a large invasive lateral removal. This piece, described in the inventory as fake, could be considered as a core.

The richest corpus was recovered at a depth of 5 m. The six bifaces are all patinated, sometimes with cracks caused by frost and a black colour, and are considered as anthropogenic. The black colour corresponds to the impregnation of sands and gravels by black ferro-manganese oxides, observed at the bottom of the sequence of the new excavations.

Two of the six bifaces were directly removed from the section where the human mandible was discovered (for instance Nos. 2143, 2144, 2145, 2146, 2148). They are diversified but most of them are largely shaped, often asymmetrical, and with final retouch on the edges for some. They measure around 15 cm long and are cordiform or lanceolate.

TABLE 4 | Technical types of flakes and platforms at Moulin Quignon (fieldworks 2016–2019) –when readable- in number.

	Cortical	Diedhral	Facetted	Flat	Punctiform
flakes				1	
Flakes with a lateral cortical back	1	3	2	21	1
Flakes with distal-lateral cortical backs				1	1
Flakes with a distal back				1	
Flakes with a distal cortical back	1	2	1	3	2
Flakes of biface				2	
Flakes of biface?		2			1
Flakes with cortex	12	12	2	43	8
Backed flakes with cortex			1	4	
Kombewa flakes				1	1
Flakes without cortex	4	7	6	29	9
Backed flakes without cortex		2	3	2	1
Flakes with a cortical butt-back	6				
Cortical flakes	2	3	1	6	2
Elongated flakes				1	1
Total	26	31	16	116	27

The Lithic Corpus From the Recent Excavations

Core Technology

The series is composed of 15 cores made on flint nodules, which is rather a low number compared to the number of flakes ($n = 254$) (**Tables 2–4**). The core/flake ratio shows a core deficit.

The organization of removals on cores indicates short debitage sequences with unipolar or centripetal removals, on one, two (orthogonal or bifacial secant) or multiple surfaces. Most of the cores, however, are largely cortical with few removals.

The nodules used were of various sizes, often with irregular shapes, and the flint is of medium quality (sometimes presence of inclusions). No particular selection of nodule morphology seems to have been applied.

The scars, as well as the diversified nodule sizes, indicate the production of flakes of disparate shapes and sizes. No core preparation is visible and debitage exploits the natural morphology of the nodule. The relatively low frequency of hinged scars on the core surfaces seems to indicate well-controlled management of knapping angles despite the low proportion of prepared striking platforms.

Most of the cores are unifacial with one (or two) series of unipolar and centripetal removals. The striking platform is cortical or with preparation limited to reducing the angle (around 60°), when necessary. Debitage produces thick flakes with a large and thick butt, and frequently uses the natural cortical convexities of core edges. Sometimes, the lateral convexities of the flaking surface are prepared by hinged removals. The core technology of these cores indicates efficiency with very limited predetermination.

Rare cores show more intensive flaking. They are unifacial, bifacial secant or multifacial, with unipolar, centripetal or crossed removals produced in one or several series. The striking platform is partially prepared with previous removals (**Figure 6**). Bifacial cores indicate flaking on two faces with two or three series of removals. Some small final removals on two cores can be considered as retouch or final debitage attempts. Two cores indicate that flaking can become independent of the natural geometry of the nodule. They show peripheral unipolar removals obtained from a prepared striking surface and could be described as "semi-tournant"-type cores. One other core surface shows additional debitage by invasive and hinged unipolar removals.

The largest core (163 mm × 150 mm × 92 mm) is a piece with three orthogonal surfaces. Two opposite surfaces and the edges of the core were flaked. Invasive centripetal removals on one face are obtained from cortical striking platforms or previous removals. Finally, peripheral and orthogonal removals are produced on part of the core periphery. Then there is alternating flaking of two orthogonal surfaces with some additional removals on the first flaked surface. The lower surface of the core shows some scars extracted from other cortical striking platforms. Traces of strong impacts on the edges, with angles close to 90°, suggest that the core was recycled as a hammerstone.

Most of the products come from on-site debitage. A large proportion of flakes are cortical, from the first phases of flaking (**Figure 7**). They measure between 40 and 80 mm long (**Table 2**). Most of them are "robust" and thick flakes with edge angles of around 70°. Cortical flakes indicate the flaking of oval or irregular nodules. Convergent unipolar or unipolar removals eliminate the cortex by a series of thick flakes. The butts indicate that striking platforms were prepared or cortical. A majority of flakes have a cortical back and some have a cortical butt-back, from the edges of the core or nodule.

Non-cortical flakes show that a longer debitage sequence can continue on the cores by unipolar, centripetal or crossed flaking. The frequency of backs for non-cortical flakes also indicates that flaking continued on core edges. Some more elongated flakes mainly result from the use of the scars and core edges. Flakes are often thick, and some are truncations of a convex or pyramidal flaking surface. Flake sections show abrupt facets and deep scars. Butts are flat, but also punctiform, dihedral and "faceted" (with more than two scars). Few flakes are hinged, confirming control of the striking platform, despite some evidence of hinged scars on

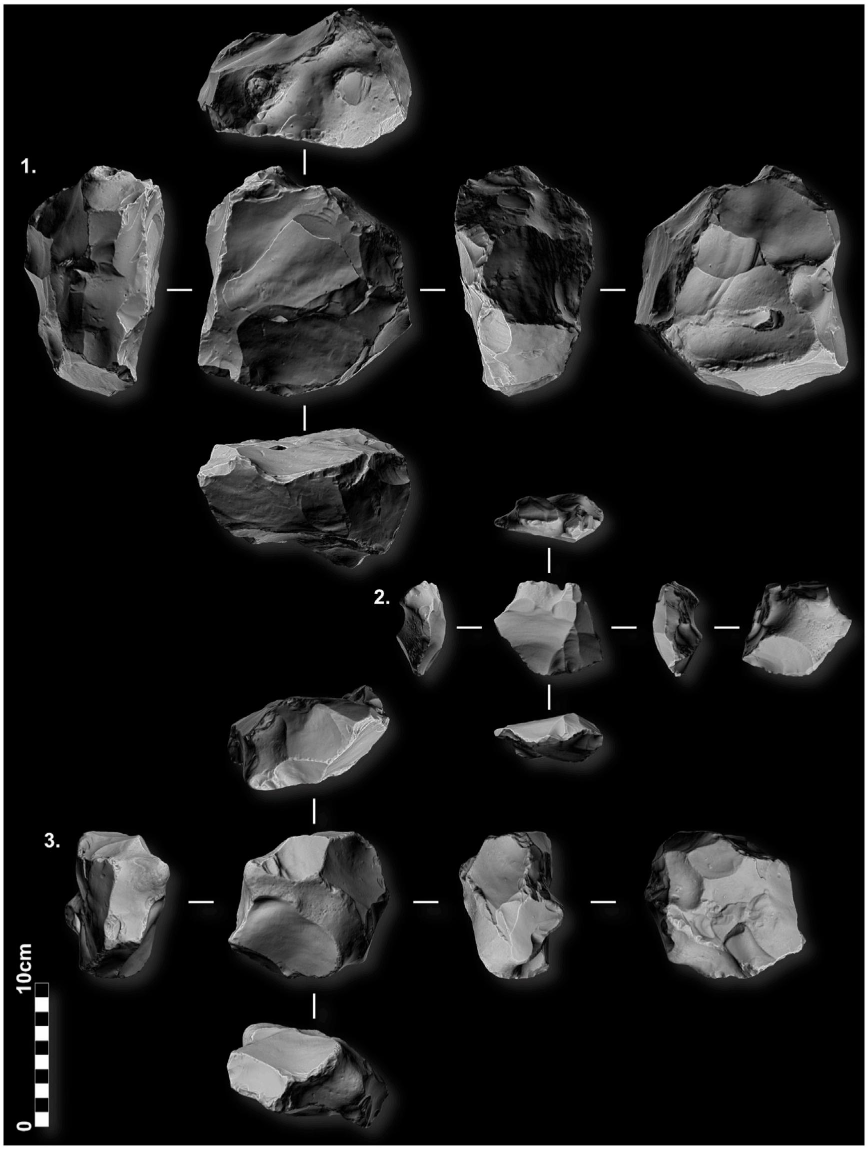

FIGURE 6 | Cores discovered at Moulin Quignon in layers Gr-n in 2019 campaign. Compléter la description en cohérence avec la bdd et le texte. Views come from the 3D models obtained by photogrammetry, reworked by a radiance scaling shader in Meshlab; sections are generated thanks to compute planar section in Meshlab. 3D models and CAD by David Hérisson.

cores. One of the main production characteristics is the presence of wide and thick butts with an acute angle (50–60°). Impact points are positioned far from core edges, as is the case for "Clactonian" type debitage (Ashton et al., 1994). We can mention two Kombewa flakes, resulting from the breakage of a nodule and the knapping of the broken surface.

Less than 31 flakes show retouch (one or more edges with marginal or irregular retouch), but only seven are unquestionably retouched: three convergent scrapers made by irregular retouch and two end scrapers on the largest elongated flake (128 mm) and a cortical flake, with retouch on both lateral edges (**Figure 7**).

Shaping of Bifaces and Other Heavy-Duty Tools

The five bifaces recovered during work in 2016–2019 display diversified shapes and shaping modes, resulting from short management strategies (one series of removals), several series of removals and possible resharpening in one case (**Figures 8**, **9**). Some parts are worked by a single series of removals, probably with a hard hammer, leaving cortical areas. Others indicate several series of removals shaping the piece first by direct percussion with a hard hammer (deep and large scars), then probably with a soft hammer or a hard hammer with a tangential

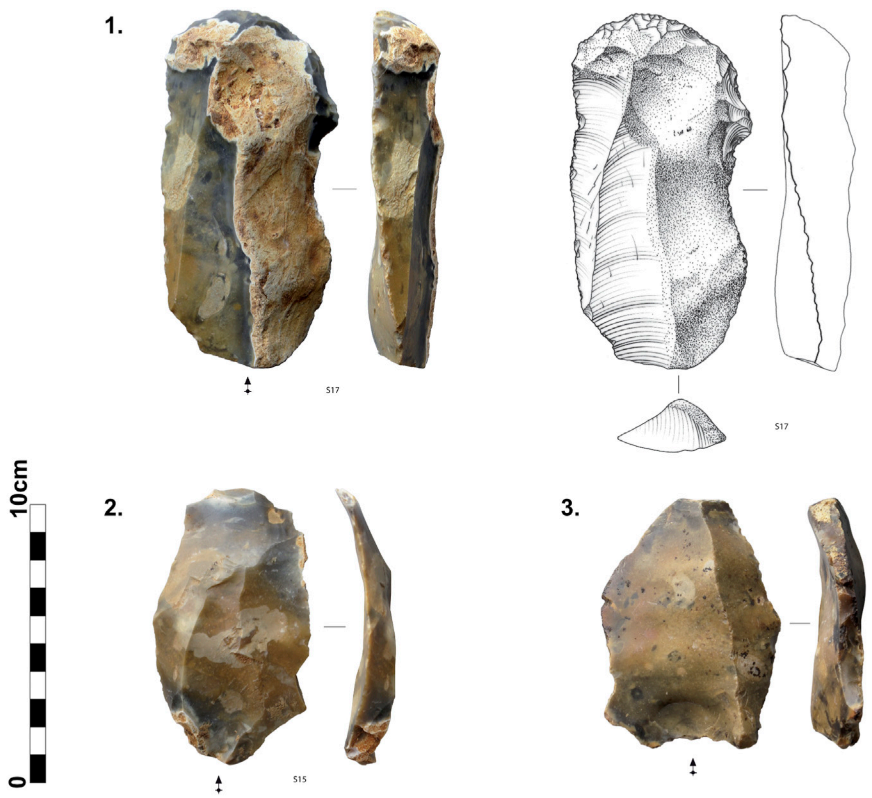

FIGURE 7 | Flakes discovered at Moulin Quignon in layers Gr-n in 2016–2019 campaign. 1: End-scrapper on cortical thick flake. 2: Fine large flake coming from bifacial shaping. 3: Non cortical flake. Photos and drawings by Stéphane Lancelot.

gesture (fine and more or less invasive removals or retouch) for the final shaping phase of the tip and/or distal edges.

- Elongated triangular biface without cortex. It is an asymmetrical piece with a lateral back created by abrupt removals. It is shaped by invasive and flat removals. Special care is taken at the extremity of the tool with small retouch/removals. It is worth mentioning an invasive removal on the base which covers a large part of one of the faces of the tool.
- Triangular and symmetrical biface with a thick, cortical base. Shaping is carried out by alternate invasive and thick removals, which manage the entire volume. Special attention is given to the tip modified by small removals and retouch covers the entire periphery. The edges are sinuous. This tool has been deeply shaped and reduced and must have been considerably longer at the beginning of the shaping process. Hard then soft hammers were used. The final removals/retouch are flat and some abrasion is visible.
- Oval and symmetrical biface with cortical residues on one side and one back. Centripetal removals cover the surfaces and particular care was paid to the extremity, which is thin and rounded. Retouch is visible all around the periphery. Tool size is similar to the size of the nodule.
- Symmetrical and broken biface made by large removals on one side. The point is broken by flexion. Transversal removals remove the base. Thick, bifacial and unifacial retouch covers the edges. Crushing is visible on the edges. The organization of removals and the cortex indicate that biface size was similar to nodule size. Fragmentation occurred during the shaping process or in the use process.
- Crudely-shaped biface by alternate shaping with large and deep removals. The extremity is modified by a small transverse removal (use?). The section is asymmetrical, which does not modify initial blank morphology. Retouch and traces of crushing are visible on the edges.

Flakes that can be related to biface shaping are very rare. They are selected by features such as a lip, reduced butt and the cross-section. This small quantity is due to the geological history of the corpus. There are no refits and no flakes from the bifaces of the series have been identified with certainty in the assemblage.

Four pieces on fragments of nodules were classified as shaped tools. These are two “rabots,” thick scrapers with abrupt retouch/removals, and two crudely-made bifacial pieces.

Comparison Between the Boucher de Perthes Lithic Corpus and the Recent Excavation Corpus

Only some bifaces can be diagnosed in the corpus found by Boucher de Perthes. This series includes a small set of well stratigraphically located pieces with labels written by the hand of Boucher de Perthes.

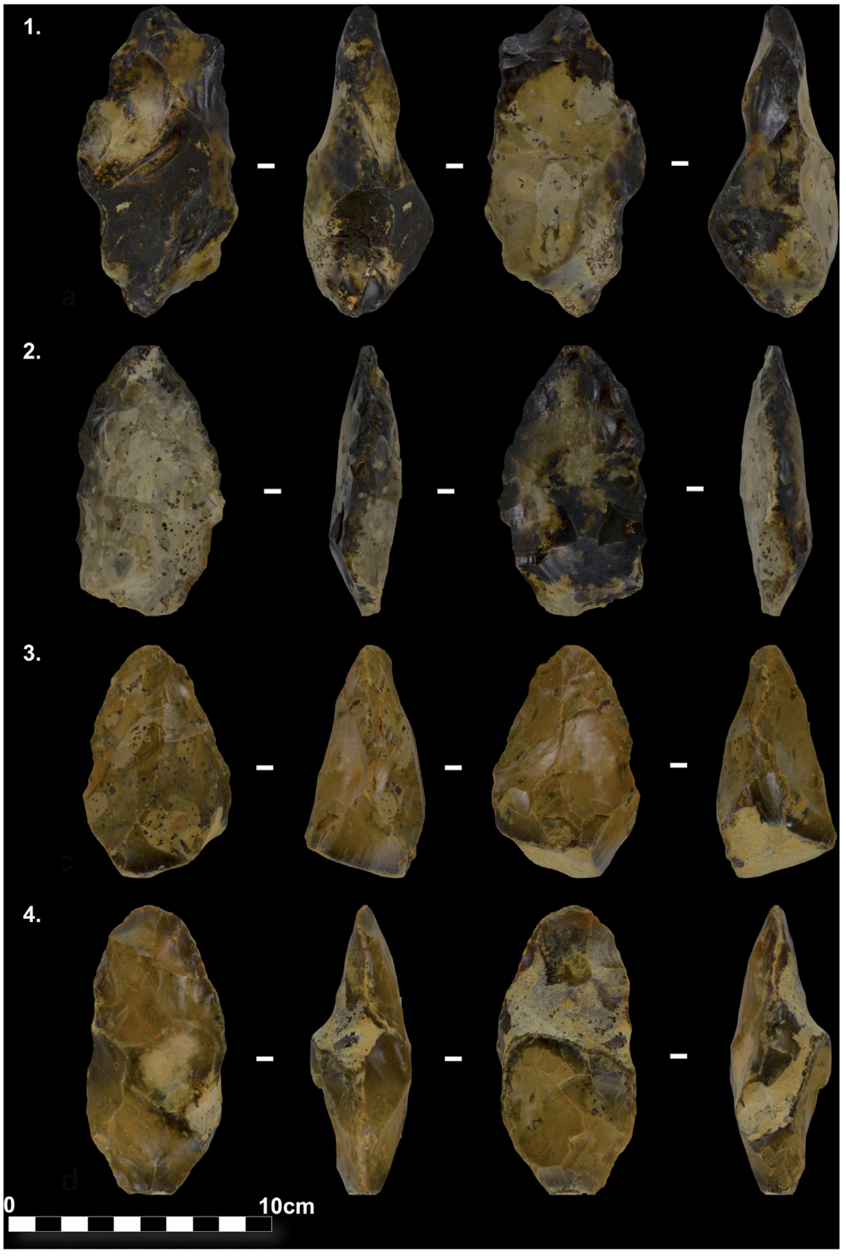

FIGURE 8 | Handaxes discovered at Moulin Quignon in layers Gr-n in 2016–2019 campaign. Views come from the 3D models obtained by photogrammetry, reworked by a radiance scaling shader in Meshlab; sections are generated thanks to compute planar section in Meshlab. 3D models and CAD by David Hérisson.

However, their position, at 4 and 5 m deep *in situ* on this site, cannot confirm their actual position in the sequence. These pieces may have been brought to the quarry by workers. However, similarities between the patina of these tools and the patina of tools from recent excavations can be observed. Biface No. 2978 from a depth of 4 m shows a face with breccia and a dark patina typical of the black layer observed at the bottom of the sequence. This black layer was also observed in the various recent test pits and during the 2017 excavation at the base of the gravels. It corresponds to a very deep impregnation of the sands and gravels by black ferro-manganese oxides forming thick coatings on the flints. No.2143, at a depth of 5 m, is covered by a greenish-yellow patina, similar to pieces from our sandy layers. No. 2144, at a depth of 5 m, is affected by frost cracks. Nos. 2145, 2146 and 2147 are patinated.

The surface aspect validates to some extent the authenticity criteria of what Falconner and his colleagues in 1863 described as an “axe” (presence of patina and polish, and smooth edges). None of them bears traces of iron (fake tools) and the few earthy residues are encrusted in the edges of the scars.

If we consider that the bifaces found by Boucher de Perthes were in place and not introduced by workers from other prehistoric sites, their technical characteristics allow us to

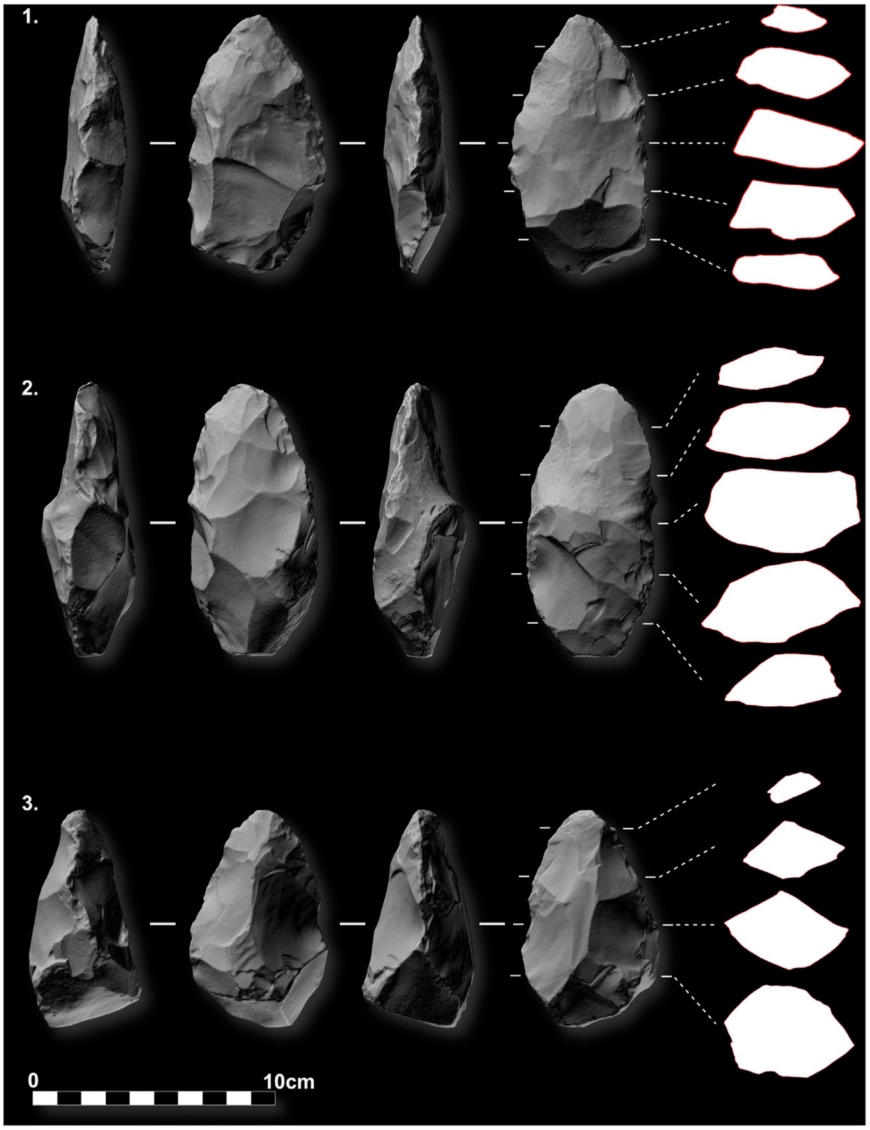

FIGURE 9 | Handaxes discovered at Moulin Quignon in layers Gr-n in 2016–2019 campaign. Views come from the 3D models obtained by photogrammetry. 3D models and CAD by David Hérisson.

observe 1) an association of not very elaborate bifaces and largely-shaped bifaces, 2) oval or cordiform tools, often with a plano-convex cross-section, with a symmetrical or asymmetrical shape, sometimes with retouch to regularize the edges.

The five bifaces found in the recent excavations show similar characteristics and, despite the small number for each series, could indirectly confirm the origin of the old series.

DISCUSSION: NORTH-WESTERN AND SOUTHERN EUROPEAN CONTEXTS FOR HUMAN OCCUPATIONS

The link between global climate variations and regional environments is difficult to establish for the time period before MIS 12. Indeed, global as well as regional palaeoclimatic data (i.e., mainly marine records) are continuous, but palaeoenvironmental data from both northern and southern Europe are still partial. Only a few archaeological sites have been identified over this period. Moreover, the paleoenvironmental proxies found in each archaeological site (e.g., micro and macro fauna, pollen grains) are often scant and of poor quality. Archaeological sites can thus only provide snapshots of local past environmental changes.

If we look at the technological strategies applied by hominins, from the earliest evidence of human occupation (1.4–1.2 Ma) to the long MIS 12 glacial event, over Western Europe, above and south of the c. 45th N., assemblages are composed of cores (including chopper-cores) and flakes or of cores (Mode 1 assemblages), flakes and Large Cutting Tools (LCTs, including bifaces, cleavers,

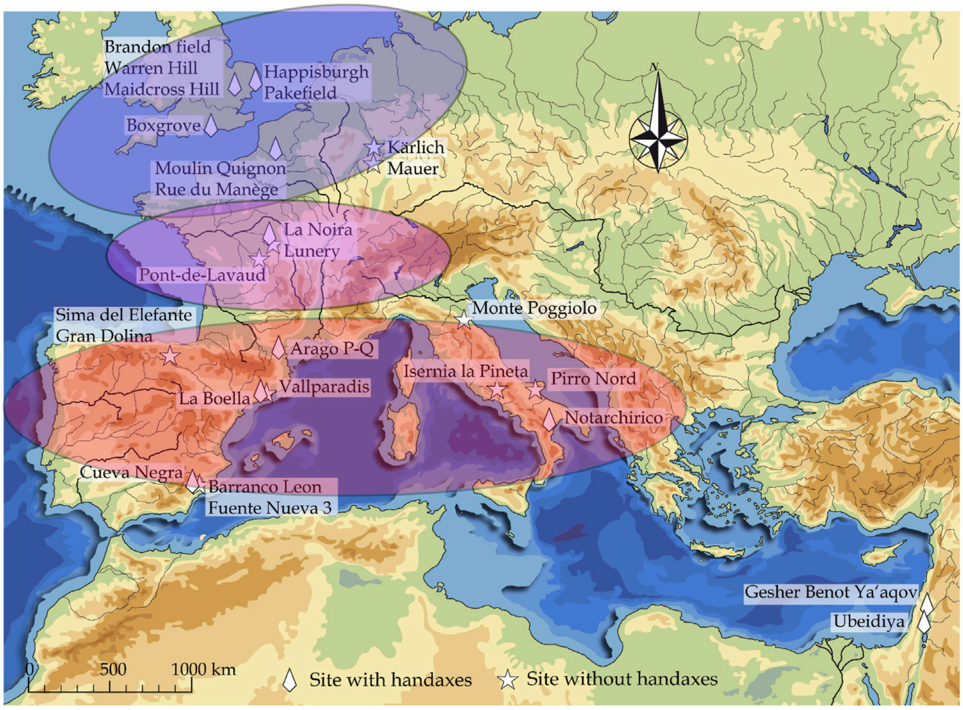

FIGURE 10 | Moulin Quignon in the North of France (North-Western biome) and the main sites in Western Europe, with or without handaxes.

bifacial tools and other shaped tools, Mode 2 and Acheulean). For some, the lack of LCTs associated to some innovations in core technology suggest that the assemblages could be also attributed to Mode 2 or in general to Lower Palaeolithic.

If we focus on some key sites in a narrower timeframe (**Figure 10**; **Table 5**), between 1 Ma and 600 ka where we observe the earliest evidence of a biface shaping in Western Europe, we observe the following strategies:

(1) Above the c.45th N:
  - Only core technologies with core-and-flake series (Mode 1): British sites of Happisburgh 3 (MIS 25–21, around 900 ka) and Pakefield (MIS 19 or 17, around 700 ka), French sites of Lunery and Pont-de-Lavaud (MIS 31, ca 1 Ma).
  - Series with core technologies and Large Cutting Tools (LCTs) (Mode 2): British sites of eastern England such as Brandon Field (MIS 15, 600–550 ka ?), French sites of Moulin Quignon (670 ka, beginning of the MIS 16) and la Noira (700–650 ka, end of MIS 17/beginning of MIS 16).

(2) South of the c. 45th N:
  - Only core technologies with core-and-flake series (Mode 1 and Mode 2): Spanish site of Atapuerca Gran Dolina level TD6 (ca 800 ka, Mode 1), Italian site of Isernia-la-Pineta (590 ka, Mode 2).
  - Series with core technologies and Large Cutting Tools (LCTs) (Mode 2): Spanish site of Barranc la Boella (1 Ma–900 ka), Italian site of Notarchirico (650–610 ka) and French site of the Caune de l'Arago, levels P-Q (532 ± 106 ka).

Available Environmental Data for the Earliest Human Occupations

Above the c. 45th North

Above the c. 45th N., the site of Pont-de-Lavaud in the centre of France yielded pollen grains associated with human occupations related to core-and-flake type assemblages and dated to 1.055 ± 0.055 Ma. Pollen grains indicate a forested environment in a very humid warm temperate climate. Hominids were therefore present during an interglacial temperate climate at this mid-latitude (Marquer et al., 2011; Despriée et al., 2018).

Plant and faunal remains from British sites such as Happisburgh 3 (MIS 21, 866–814 ka, or MIS 25, 970–936 ka) and Pakefield (MIS 19 or MIS 17, about 750–680 ka) attest however that the climate was rather continental and cool for occupations dated between MIS 25 and 17 at this latitude (Parfitt et al., 2005; Parfitt et al., 2010; Farjon et al., 2020). These two sites yielded series of cores and flakes, with no evidence of biface production. At Happisburgh 3, artefacts are associated with *Pinus* and *Picea* pollens and conifer wood and pine cones, indicating regional conifer-dominated forest. Temperature estimations point to mean summer temperatures between 16 and 18°C and mean winter temperatures between 0 and −3°, with similar conifer-dominated woodland to that of present-day southern Scandinavia. Local grassland is indicated by the range of grazers (*Equus suessenbornensis,* Bovidae and *Microtus* spp.) and indirectly, by preserved pollen from hyaena coprolites. Mammals include *Mammuthus* cf. *meridionalis,* Bovidae, *Equus suessenbornensis* and at least two species of *Mimomys.*

TABLE 5 | Synthetic data on Northwestern and Southern sites.

	Raw materials	Main features of the debitage	Independency of the stone shape on cores	Preparation of a striking platform	Flake-tools	Bifaces	Heavy-duty component	Percussion	Envrionmental data	References
Happisburgh 3 (UK) 900 ka	Local flint nodules	Unipolar Centripetal Thick flakes	no	Plain butts	Numerous tools	no	no	Freehand hard hammer	Conifer forest Grassland	Parfitt et al. (2010)
Pakefield (UK) 700 ka	Local good quality black flint nodules	Unipolar Centripetal Multidirectional cores Thick flakes	no	Plain butts	some	no	no	Freehand hard hammer	Broad-Leaf woodland	Parfitt et al. (2005)
Brandon Field (UK) MIS 15/14	Local flint nodules	?	?	?	?	Numerous Crudely-made bifaces Ovate bifaces	?	Freehand hard hammer Soft hammer (LCTs)?	Interglacial?	Moncel et al., 2015
Moulin Quignon (FR) 670 ka	Local flint nodules	Unipolar-bipolar convergent centripetal cores Thick and large flakes	One centripetal and orthogonal core	Plain and cortical butts	Around 10%	N = 5 Crudely-made tools and pointed bifaces	Some on fragments of nodule	Freehand hard hammer Soft hammer (LCTs)?	Cold event	Antoine et al. (2019)
Lunery (FR) 1,1 Ma	Local Jurassic silicifications Cubic blocks	Unipolar Crossed Unipolar convergent cores Small flakes	no	Rare	4%	no	Some on blocks	Freehand hard hammer	?	Despriée et al. (2018)
Pont-de-Lavaud (FR) 1,1 Ma	Local quartz blocks and pebbles	Unipolar Bipolar Multidirectional cores Thick flakes and fragments	no	Rare	Few	no	One bifacial tool	Freehand hard hammer Anvil percussion	Forested Warm humid	Despriée et al. (2018)
La Noira (FR) 700 ka	Local millstone slabs	Unipolar Centripetal cores	Some bifacial centripetal cores	Plain and cortical butts	23.4%	N = 8 bifaces (new fieldworks) Diversity of crudely-made	Numerous and divers tools on slab	Freehand hard hammer Soft hammer (LCTs)	End of interglacial Beginning of a glacial event	Moncel et al. (2020a)

(Continued on following page)

TABLE 5 | (*Continued*) Synthetic data on Northwestern and Southern sites.

	Raw materials	Main features of the debitage	Independency of the stone shape on cores	Preparation of a striking platform	Flake-tools	Bifaces	Heavy-duty component	Percussion	Envrionmental data	References
						tools and bifacial tools				
Stratum a		Unipolar and centripetal cores				Largely-shaped bifaces				
Barranc de la Boella (SP)	Local various stones	Unipolar	no	Rare	Some Denticulates, notches	N = 2	Some pebble-tools	Freehand hard hammer	Temperate	Vallverdú et al. (2014)
1 Ma-900 ka 3 localities		Centripetal cores Large and small flakes				Crudely-made 1 pick 1 cleaver-like on flake	Hammers Chopper-cores			Mosquera et al. (2015)
Sima del Elefante TE7-TE16 (SP) 1.2 Ma	Diversified local stones Chert and others	Rare artefacts				no	no		Warm, humid	De Lombera-Hermida et al. (2015)
Gran Dolina TD6 (SP) 800 ka	Local and semi-local Neogene flint dominant quartz	Unipolar Centripetal cores Large and small flakes	no	No	6%	no	Some crudely-made on blocks	Freehand hard hammer Anvil percussion	Warm, humid Woodland, steppe transition	Ollè et al. (2013)
Notarchirico (IT)	Diversified local stones	Unipolar	no	Plain and cortical butt	Around 10%	Diversity of crudely-made bifaces and largely-shaped bifaces	Pebble-tools (some pointed) on limestone	Freehand hard hammer	Interglacial and glacial events	Moncel et al. (2019), Moncel et al. (2020a)
610–695 ka	Chert and radiolarite nodules, limestone pebbles	Centripetal Multidirectional cores Retouched small nodules Small flakes and backed flakes							Temperate and dry (top)	
Isernia-la-Pineta (IT)	Local flint and limestone	Unipolar	Discoid-type cores	Plain and cortical butts	Around 7%	no	Numerous pebble-tools on limestone	Freehand hard hammer	Woodland steppe	Gallotti and Peretto, (2015)
Level t.3c 590 ka		Centripetal cores Small flakes Retouched fragments								

(Continued on following page)

TABLE 5 | (*Continued*) Synthetic data on Northwestern and Southern sites.

	Raw materials	Main features of the debitage	Independency of the stone shape on cores	Preparation of a striking platform	Flake-tools	Bifaces	Heavy-duty component	Percussion	Envrionmental data	References
Caune de l'Arago Levels P-Q 550 ka	Local to 15–30 km long Quartz, quartzite, flint and others	Discoid-type cores Unipolar cores Small flakes	no	Plain and cortical butt	8%	Diversified bifaces and cleavers on flake	Pebble-tools on quartz	Freehand hard hammer	Interglacial	Barsky and Lumley, (2010)

An assemblage of 78 flint cores, flakes and flake-tools has been excavated according to studies from fluvial gravels and laminated estuarine sands and silts or glaciomarginal fans desposited in a proglacial lake complex (Cromer Forest-bed Formation CF-bF) (Gibbard et al., 2009; Gibbard et al., 2011; Gibbard et al., 2012; Gibbard et al., 2018; Hijma et al. 2012; Parfitt et al., 2010; West, 2019; West et al., 2019; Turner et al., 2020; Gibbard et al., 2021; West and Gibbard, 2021).

At Pakefield, macro remains and fauna from the Cromerian Forest-bed indicate warmer summers and mild winters (between 18 and 23°C for summer) with broad-leaf woodland. Macro-remains (*Trapa natans*, *Salvinia natans* and *Corema album*), beetles (*Cybister lateralimarginalis*, *Oxytelus opacus* and *Valgus hemipterus*) and the presence of *Hippopotamus* indicate warmer summers and mild winters (between 18 and 23° for summer). *Mammuthus trogontherii*, *Stephanorhinus hundsheimensis*, *Megaloceros savini*, *M. dawkinsi*, *Bison cf. schoetensacki*, and carnivores (*Homotherium sp.*, *Panthera leo*, *Canis lupus* and *Crocuta crocuta*) make up the faunal assemblage. Pollen analysis indicates an interglacial with broad-leaf woodland including *Carpinus*. *Mimomys savini* and *M. aff. Pusillus* are both present.

The British sites of Brandon Fields, Maidscross Hill and Warren Hill yielded evidence of bifacial technology on flint. The age of the associated sediments was recently dated by ESR-quartz to 550–600 ka suggesting an age of MIS 15-14 for the earliest bifaces in Great Britain (Voinchet et al., 2015; Lewis et al., 2021). However, microfaunal data are not in keeping with the ESR dates, and place these sites in MIS 13 under a landscape of boreal species and open grassland (Candy et al., 2015).

At la Noira, in the centre of France, hominids were present at the end of MIS 17 and the beginning of MIS 16 and disappeared from the area when it became too cold (Despriée et al., 2011; Moncel et al., 2020c). The site is located along the Cher River, a tributary of the Loire River. The substratum of Tertiary lacustrine limestone (stratum a) is overlain by five strata. A coarse slope deposit (Stratum b) is covered by two sequences of fluvial sediments (Strata c and d). The artefacts are associated with the basal coarse sand of stratum b, the lower part of which consists of an accumulation of local "millstone" in Oligocene lacustrine limestone. The earliest archaeological level is located at the bottom of the sequence. The position of the artefacts between the deposition of slope materials on the limestone bedrock and later phases of gelifluction and cryoturbation, would suggest that hominins were present after the period of river incision at the beginning of a cold climatic stage. ESR dates (mean age of 655 ± 55 ka) place this stage at the beginning of MIS 16 (Moncel et al., 2013; Moncel et al., 2015, Moncel et al., 2020c; Moncel et al., 2021a).

Below the c. 45th North

At the Caune de l'Arago (France), levels P-Q are dated back to 532 ± 106 ka by ESR/U-series (Falguères et al., 2015). Sedimentological analysis shows that the Unit I deposit is essentially composed of sands blown into the cave by strong north-eastern winds during a dry and cold phase of MIS 14. The levels yielded assemblages with bifaces (Barsky and Lumley, 2010;

Barsky, 2013). The faunal spectrum includes *Ursus deningeri*, *Cuon priscus*, *Vulpes vulpes*, *Lynx spelaeus*, *Panthera cf. pardus*, *Equus mosbachensis*, *Stephanorhinus hemitoechus*, *Bison* sp., *Ovis ammon antiqua*, *Hemitragus bonali*, *Rangifer tarandus* and *Cervus elaphus* (Moigne et al., 2006). Horse (28%), reindeer (20%) and bear (28%) are the most abundant taxa indicating an open and steppe landscape. The cave was alternately a bear den or a den for other carnivores and a habitat for short-term human occupations.

In Spain, at Atapuerca, Sima del Elefante and Gran Dolina yielded several archaeological levels from this period. At Sima del Elefante, lower units TE7 to TE16 show reversed polarity magnetization attributed to the Matuyama Chron, confirmed by cosmogenic nucleids with 1.2 Ma to TD9 (Parès et al., 2006; Carbonell et al., 2008; de Lombera-Hermida et al., 2015). The occupations were characterised by a humid and warm climate before a period of cooling recorded at MIS 22 (ca. 900 ka). Pollen shows the presence of *Pinus sylvestris*. Unit TE16 is dated to 804 ± 47 ka and 864 ± 88 ka. The luminiscence ages obtained for TE17 are 724 ± 43 ka and 781 ± 63 ka.

Layer TD6 at Gran Dolina, composed of 2–2.5 m of blocks and gravels in a poor clayey matrix, has been divided into three lithostratigraphical units and yielded hominin remains (Carbonell et al., 2005; Carbonell et al., 2010). TD6 has a pre-Matuyama negative polarity (>0.78 Ma, MIS 21) (Blain et al., 2013; Parès et al., 2013) confirmed by biostratigraphy and radiometric dating by electron spin resonance of optically-bleached quartz and U-series methods (Rodriguez et al., 2011; Duval et al., 2018). Sub-unit TD6-2 is characterised by warm and humid climatic conditions (continental Mediterranean climate) (Rodriguez et al., 2011). The landscape indicates open woodland and steppe. This can be correlated with the transitional phase of forest development during a cold to warm climatic transition (possibly correlated with the MIS 22/21 transition). A moderate increase in the presence of open dry taxa occurs in several samples from sub-unit TD6-3 to TD6-1 and indicates steppe habitats in a mosaic environment.

The site of Barranc de la Boella in Spain is located in a fluvio-deltaic area with an aquatic environment. Six lithostratigraphic units (Units I–VI, from bottom to top) are described (Mosquera et al., 2013; Vallverdú et al., 2014; Mosquera et al., 2015; Mosquera et al., 2016), including one with crude bifacial tools. Fieldwork has been carried out in three different localities, at the same stratigraphic position: Pit 1 (P1), la Mina (LM), and el Forn (EF). Fossils recovered up until now are almost exclusively from Unit II (Vallverdú et al., 2014). The P1 faunal sample is almost entirely composed of mammoth remains, associated with a lithic sample of more than 100 remains, including a pick and a cleaver cited as proof of the early arrival of Acheulean technology in Europe. A solid geochronological age for the lithic assemblages found in BB Unit II could indicate a position in the late Early Pleistocene or late Matuyama Chron (0.96–0.78 Ma). The presence of *Mammuthus meridionalis* and the morphology of *Mimomys savini* molars from the top of Unit II at the three localities support the age of the archaeological deposits. The faunal assemblage of level 2 (Unit II) of the Pit 1 locality is dominated by *Mammuthus meridionalis,* associated with a few *Dama* cf. *vallonetensis* and *Equus* sp. (Pineda et al., 2015; Pineda et al., 2017).

Notarchirico in Italy is a 10-m-thick fluvial-derived sedimentary sequence rich in volcanic materials from the Monte Vulture stratovolcano (Piperno, 1999; Lefèvre et al., 2010). Hominins circulated regularly along these water channels or lakeshores. Several radio-isotopic methods (ESR and $^{40}Ar/^{39}Ar$) were applied to quartz grains and volcanic minerals (mainly sanidines and clinopyroxenes) in the sediments. The results constrain the period of occupation of this site to between 695 ± 6 ka and 614 ± 12, spanning the entire cold stage MIS 16 and the end of MIS 17 (Pereira et al., 2015; Moncel et al., 2020b). The site thus records one of the earliest known occurrences of bifacial technology in Southern Europe (levels B, D, F, G) (Piperno, 1999; Moncel et al., 2020a; Santagata, et al., 2020). Raw material procurement and core technology are similar throughout the sequence and focus on the production of small flint end-products. The oldest handaxes found at Notarchirico (levels F and G) are now securely dated to more than 670 ± 4 ka and prove that hominid populations lived there as early as at the beginning of MIS 16 and at the end of the MIS 17. The faunal remains found in the lower levels (E/E1, F, and G) are *Elephas antiquus*, *Dama clactoniana*, *Bos primigenius*, and *Bison schoetensacki.* The faunal assemblage of Notarchirico belongs to the "Ponte Galeria" faunal unit. From the microfaunal point of view, micro-mammals indicate a dry climate typical of the Middle Pleistocene glacial period in the Italian peninsula. Results from the top of the sequence show that vegetation was characteristic of open and cold environmental conditions with *Poaceae* meadows (Piperno, 1999).

The stratigraphy of Isernia-la-Pineta (Italy), near Notarchirico, is composed of five units (Gallotti and Peretto, 2015). Unit 3 contains the archaeological deposits and is sub-divided into three sub-units. Unit 3a is the richest level, composed of a high concentration of flint and limestone artefacts (without bifaces). Recent $^{39}Ar/^{40}Ar$ dates of 583–561 ka corresponding to the MIS 15/MIS 14 transition were proposed by Peretto et al. (2015) for this site, based on more than 90 single crystal sanidine dates. The faunal list is composed of *Elephas (Palaeoloxodon) antiquus*, *Hippopotamus* cf. *antiquus*, *Stephanorhinus hundsheimensis*, *Bison schoetensacki*, *Praemegaceros solilhacus*, *Cervus elaphus* cf. *acoronatus*, *Dama* cf. *roberti*, *Capreolus* sp., *Sus scrofa*, *Hemitragus* cf. *bonali*, *Panthera leo fossilis*, *Panthera pardus* and *Homo*. The most abundant carnivore remains are those of *Ursus deningeri* (Thun Hohenstein et al., 2009; Peretto et al., 2015). The large number of herbivores indicates that the Isernia region was an area of open vegetation of woodland steppe, rich in pastures, with bison herds and numerous pachyderms during the MIS 15/MIS 14 period (Thun Hohenstein et al., 2009; Pineda et al., 2020). This kind of environment indicates a climate with a long and arid season coupled with a shorter one with concentrated annual rainfall (Lebreton, 2002; Orain et al., 2013).

Hominin Strategies in North-Western Europe

The technical features of the flint industry identified in the Cromer Forest bed formation at Happisburg 3 and Pakefield (Great-Britain, ~900 and 700 ka) are difficult to evaluate due to the limited number of lithic pieces in local flint (Parfitt et al., 2005; Parfitt et al., 2010). However, it is possible to observe: 1) thick platforms and open angles on flakes, 2) unipolar and centripetal removals on flakes, 3) opportunistic cores on flint nodules. These features are common to the French sites of Lunery and Pont de Lavaud dated around 1 Ma ago (Despriée et al., 2017a; Despriée et al., 2018) (**Table 5**). At Pont-de-Lavaud (de Lombera-Hermida et al., 2016; Despriée et al., 2018), debitage is only on quartz pebbles with short sequences of freehand percussion or anvil percussion (bipolar debitage).

These features are similar to those of the Moulin Quignon corpus of flakes and cores, perhaps due in part to the common use of local flint nodules, except for the quartz series of Pont-de-Lavaud. The flake reduction process consists mainly of knapping large flakes. Cores indicate either crude and opportunistic flaking, using the natural blank shape on one or multiple surfaces. Some cores show no links with nodule shape and thus indicate the limited constraints of blanks and a degree of independence from the raw material.

At the French site la Noira (Centre of France) (stratum a, 700 ka) (Moncel et al., 2013; Moncel et al., 2015, Moncel et al., 2020c), hominins used local millstone slabs, a type of silicification in Oligocene lacustrine limestone, available in huge quantities on the riverbank in deposits covering the valley slopes. Hominins recovered millstone quadrangular slabs *in situ* for flaking or shaping. They focused on this raw material despite the presence of some other materials, in the same way as at Moulin Quignon. Slab shape is conducive to the first phases of debitage and shaping processes with the use of the flat natural surfaces. Cores and bifaces are always on good-quality stone, suggesting that stone selection was linked to production and management aims. The selection of the thickness and the shape of the slab or slab fragment was a priority for bifaces and structured cores. This selection indicates the flexibility and adaptability of hominins to the diversity of available slabs. Core technology is the predominant activity at the site, with two main "chaînes opératoires"; one devoted to the production of small flakes and the other to large flakes.

For LCT technology, the British sites of Brandon Fields, Maidscross Hill and Warren Hill, dated to MIS 15/14 (Voinchet et al., 2015; McNabb et al., 2018; Lewis et al., 2021), yielded flint bifaces made by deep removals and thinner tools (oval, cordiform) made by a series of removals with final working of the cutting edges and the tip. All the assemblages are made on locally available flint nodules from fluvial gravels (Bridgland and White, 2015; Moncel et al., 2015). These series are made up of two groups of bifaces with varying ratios, with crudely fashioned bifaces made with a hard hammer and thin ovates and cordiform bifaces (made with a soft hammer with final retouch, with a symmetrical shape and cross-section, sometimes with a "tranchet flake" removal across the tip).

These features are similar to the bifaces found at Moulin Quignon, with diversified shapes and shaping modes.

At la Noira, stratum a (700 ka), the assemblage combines two groups of artefacts: one with high levels of investment and complexity (bifaces, small flakes), and one showing less complex, opportunistic and expedient behaviour (partial tools, cleavers, heavy-duty tools, large flakes). As at Moulin Quignon, shaping technology produces tools with varied shapes and more or less invasive removals. The material indicates the ability to manage the contour and biconvex symmetry and shows that standardized and structured rules were applied even though the morphological results are diverse. The shape of some final removals may possibly indicate the occasional use of a soft hammer (some thin and invasive removals). Cross-sections are plano-convex or symmetric, regardless of categories and the final morphological result (Garcia-Medrano et al., 2022). They attest to the limited role of slab morphology. The final retouch could represent resharpening in some cases and confirms controlled tool edge management. The use of elongated and thin slabs could explain the longer size of the bifaces compared to Moulin Quignon.

Are North-Western Technological Strategies Similar to Southern Traditions?

The lithic series from level TD6 of Gran Dolina (Atapuerca, Spain, ~0.8 Ma; Falguères et al., 1999; Parés et al., 2013; Duval et al., 2018) are made from all the available suitable raw materials from the surrounding areas. Neogene flint is the most abundant rock type and large blocks were flaked outside the cave (Carbonell et al., 1999; Mosquera et al., 2018). Few of them are large flakes, and they never exceed 10 cm. Core technology is mainly multifacial and orthogonal with no striking platform preparation. Bipolar exploitation on an anvil appears to be reserved for quartz (Ollé et al., 2013). Retouched thick flakes, mostly on flint, total 6% of the artefacts.

At Barranc de la Boella, Spain (Vallverdú et al., 2014; Mosquera et al., 2015), the localities yielded mainly flakes and cores, but also pebbles (hammerstones), pebble tools and chopper-cores on various local stones. Debitage is unipolar or centripetal, adapted to stone shapes with rare preparation. There are, in this case, some crudely-made LCTs, including a pick and a cleaver-like tool on a large flake, indicating sporadic bifacial shaping.

One of the earliest occurrences (levels B, D, F, G) of bifacial technology in Southern Europe is found at Notarchirico, Italy, (Piperno ed, 1999; Moncel et al., 2019; Moncel et al., 2020a). Raw material procurement is local and core technology is similar throughout the sequence, focusing on the production of small flint end-products by the freehand knapping of small flint nodules of chert or limestone pebbles. Raw material shape strongly impacts core technology. Flint end-products and cores (20–40 mm) are small in size. Retouch modifies the initial shape of the small flakes. It is often abrupt, in particular on the small retouched nodules which are directly retouched.

The diversified heavy-duty component displays little standardization and include numerous pointed chopping-tools and rare pseudo-cleavers on limestone pebbles. Hominins used local cobbles/pebbles, available in large quantities along the lakeshore. Some bifaces on quartzite, limestone and flint pebbles or flakes are bifacially shaped by more or less invasive series of deep removals, and then, in some cases, rectified by a second series of small removals on the tip. Cutting edges are irregular and the cross-section of bifaces is asymmetrical. They are rather small in size (on average, 100–120 mm long) compared to Moulin Quignon and la Noira.

The slightly younger assemblages of Isernia-la-Pineta level 3 (585 ± 1 ka; Peretto et al., 2015; Pereira, 2017), did not yield bifaces but contain an abundant heavy-duty component on pebbles and evidence of more complex debitage management (Gallotti and Peretto, 2015; Lugli et al., 2017). The lithic assemblage corresponds to well-established mental templates despite the lack of bifaces. Knappers mainly used a discoid knapping method, regardless of the size and shape of the original blank, for producing medium-sized flakes that could be retouched into tools.

At the Caune de l'Arago (France), in levels P-Q (MIS 14), discoidal working was applied to quartz or siliceous stone cobbles from 15–30 km away. Retouched flakes are abundant and mainly pointed. Bifacial tools on a variety of raw materials include well-worked bifaces of various sizes with overall volume management by a series of invasive bifacial removals and with final retouch. There are also some cleavers on flakes (Barsky and Lumley, 2010; Barsky, 2013).

Common or Variable Traditions Over Western Europe Whatever the Environmental Context?

The comparison of the lithic assemblage of contemporaneous sites shows shared behavioural traits despite very different geographical locations and mineral environments, with only flint and siliceous stones for the northwest and diversified stones for the south. This tends to suggest a common cultural background throughout Western Europe, regardless of climatic conditions, and possibly among a metapopulation.

We observe: 1) the predominant use of local raw materials and no evidence of stones brought to sites from distant outcrops, 2) occasional complex large and small flake production (core technologies), 3) adaptation to stone constraints suggesting flexibility and some evidence of flaking independently of stone geometry, 4) low ratio of bifaces, when present, and association of elaborate bifaces and partial bifacial tools, 5) diversity of shaping modes and forms for bifaces and bifacial tools (non-standardization) with some evidence of soft percussion, 6) lack of cleavers on flakes in north-western territories, and 7) rare use of large flakes for making the heavy-duty component or for knapping (little evidence of fragmentation of the reduction processes).

Location and Type of Site

The available sites are mainly open-air habitats beside rivers, lakes or swamps, except some sites in caves. This may be due to the low number of sites for this long period of time and conservation conditions. However, it may also indicate common patterns of territory and resource management. Regardless, such locations allow for easy access to quantities of local raw materials, as the sites are located on shores with abundant stones, and herbivore carcasses. Faunal remains indicate, when preserved, accumulations of large herbivores, including megaherbivores, along rivers and possibly scavenging and butchery activities in competition or not with carnivores (i.e., Barranc de la Boella, Notarchirico, Isernia-la-Pineta) (Piperno, 1999; Vallverdu et al., 2014; Gallotti and Peretto, 2015; Mosquera et al., 2015; Pineda et al., 2017; Moncel et al., 2020b). When visible, cut marks and fragmented bones demonstrate meat processing, butchery and scavenging on herbivore carcasses of different sizes, including megaherbivores (Pineda et al., 2015; Pineda et al., 2017; Pineda et al., 2020). Sites seem to be either multi-activity sites (la Noira; Hardy et al., 2018) or specialized sites (possibly scavenging sites at Isernia-La-Pineta (Longo et al., 1997; Thun Hohenstein et al., 2009; Pineda et al., 2020). They point either to mobile groups using local raw materials with little evidence of semi-local stone procurement, or less mobile groups with strong ties to a specific place and environment (Gallotti and Peretto, 2015; Mosquera et al., 2015; Ollé et al., 2016). Isotopes of strontium on the human tooth of Isernia-La-Pineta indicate the relatively limited mobility of the corresponding individual (Lugli et al., 2017).

No correlations have been established at la Noira between types of tools and function, and crudely-made bifacial tools appear to have been used in the same way as bifaces (Hardy et al., 2018). This suggests that the lithic assemblage could represent above all a cultural package, and not merely tool kits devoted to specific functions. Sites described as butchery sites for large herbivores of the same age indicate that small flakes were widely used and were possibly as valuable as heavy-duty tools for these activities (for instance Isernia-La-Pineta in Italy, Thun Hohenstein et al., 2009; Pineda et al., 2020).

Raw Materials

Raw material procurement is mainly local and related to the type of site (along water areas and rivers). Hominins used various available stones, such as cubic blocks, slabs, nodules or cobbles/pebbles and selected stone quality or thickness depending on the type of activity (Moncel et al., 2020c; Santagata et al., 2020). Medium or large-size nodules or slabs of local flint are used at Moulin Quignon and millstone slabs at la Noira while small chertlocal nodules were recovered at Notarchirico, mainly for debitage or direct retouch. Limestone pebbles are collected à Notarchirico for pebble tools and LCTs. At Moulin Quignon, all the parts of irregular flint nodules were used, even some rounded extremities. Nodule quality is mainly good. At la Noira, raw material quality seems to have been a criterion for selection, and slabs with no evidence of frost cracking were chosen (Despriée et al., 2016; Moncel et al., 2020a). Three main lithotypes were identified at Notarchirico for the small nodules used for the debitage or direct retouch: silicified calcarenites (flysch chert), nodular chert (carbonate platform) and radiolarite (basin) (Synthem of Palazzo San Gervasio (Eramo et al., in Moncel et al., 2020b). No clear selection of a specific type of chert or radiolarite is observed, whatever the occupation phase. Selection seems to have focused on nodule size and shape, for flaking or direct retouch (thick and flat small nodules for abrupt and denticulate retouch). At Pont-de-Lavaud, quartz was used, perhaps as a result of its abundance near the site (Despriée et al., 2018). The only exception is the Caune de l'Arago with some long-distance stones collected in a perimeter of 15–30 km, especially for debitage and LCTs (Barsky, 2013).

Core Technologies

Flaking comprises long and short sequences of removals, showing a diversity of hominin skills and cognition (unifacial and multifacial, bipolar or discoid-type). However, flaking sequences cannot always be considered as expedient. We observe adaptation to the shape of the blank with common rules, even on quartz. These rules indicate flexibility and a selection of stone shape for the best results. Platforms are prepared if necessary. Some reduction sequences are more structured and more independent of blank shape and fully managed on good-quality stones, as clearly observed at la Noira, Moulin Quignon and the slightly younger site of Isernia-la-Pineta.

Product size is highest at la Noira and Happisburgh (flakes >145 mm), as a result of flaking nodules or slabs, and smallest at Moulin Quignon on medium-sized nodules. At Notarchirico, the use of the small available nodules results in very small flakes (10–20 mm) and very small and thin cubic nodules are sometimes directly retouched. However, there is not always a strict correlation between the natural blank and product size. Small flakes (40 mm long) are also produced at la Noira on millstone cores and large flakes (80–100 mm long) are obtained from large cobbles at Notarchirico (**Supplementary Figures S1–S3**).

Platform angles are acute for plain and thick butts at Moulin Quignon, Happisburgh 3 and Pakefield, and more obtuse (80–90°) on slabs at la Noira and small cubic nodules at Notarchirico. The impact of stone shape alone cannot explain production aims. We observe thicker and more robust flakes in the northwest with acute retouched and unretouched cutting edges. Relationships with activities must be examined.

The ratio of flake-tools differs (mainly unilateral or bilateral retouch and some notches) depending on the site and TD6 and Happisburgh 3 seem to be an exception for Mode 1 series. In most sites, flake-tools bear one or several retouched cutting edges. Angles are mainly dependent on the type of raw material, and are lower for flint with acute unretouched angles. The diversity of the number of retouched edges, creating simple, multiple or an association of simple tools on the same blank, can be correlated to needs. At the Caune de l'Arago, discoidal working was applied to quartz or siliceous stone cobbles from 15–30 km away. Retouched flakes are abundant and mainly pointed.

Bifaces and Large Cutting Tools

The number of bifaces with overall volume management is low for each site and we cannot assess whether or not these tools were more mobile than other tools. Raw materials are local. Despite the small numbers, the series associate various intensities of shaping, with crudely-made tools and very reduced bifaces. The artefacts from la Noira illustrate the diversity of the heavy-duty component, with diverse heavy-duty tools made on irregular fragments of slabs (Iovita et al., 2017; Moncel et al., 2020c).

Series are characterised by the diversity and lack of standardization of bifacial tools and the heavy-duty component, although some are more homogeneous, due to the raw materials. Cutting edge angles vary depending on the sites and stones, as does biface size, which is smaller at Notarchirico, longer at la Noira. However, we have to keep in mind that some bifaces, like at Brandon Field, Moulin Quignon and la Noira, may have undergone resharpening, resulting in decreased tool size. Raw material size could also partly explain the diversity of biface size (**Supplementary Figure S4**). At Caune de l'Arago, bifacial tools on a variety of raw materials include well-worked bifaces of various sizes with overall volume management. There are also some cleavers on flakes.

Strategies and Behavioural Solutions for North-Western Europe?

The limited number of sites and the diversity of contexts hinder comparisons of the specific features of each site and the investigation of adaptation to colder climates and environmental contexts. Stone types do not seem to be associated with specific flaking methods, except for quartz. Debitage modes on siliceous rocks are similar, with adaptation to stone shape (slabs, nodules. . .). Flaking products differ according to raw material size, ranging from large flint flakes in the northwest of Europe to mainly small flakes in the South of Italy. Observations are similar for LCT management and production. We also observe a wide diversity of cutting edge angles among the light and heavy-duty component, possibly pointing to diverse functional tool kits and cultural packages. The diversity of skills, routines and strategies among populations in Western Europe between 1 Ma and 600 ka seems to have been favourable to adaptation to varied environmental contexts.

In Moncel et al. (2018a), we discussed current data from the archaeological record for which the climatic context cannot be accurately assessed. The link between global climate variations and regional environments is difficult to establish for this period of time. During the main Middle Pleistocene glacial periods such as MIS 16 and MIS 12, the ice sheet probably had an impact on hominin occupations in Eurasia, erasing northern evidence of human sites from previous interglacials. In addition, many sites are not dated accurately enough to be confidently correlated with regional climatic and palaeoenvironmental records. The position of a human occupation cannot always be strictly linked to a glacial or interglacial solely on the basis of age and stratigraphic position. On the other hand, faunal remains and thus biostratigraphy are markers of specific environmental conditions. Furthermore, occupation duration (i.e., seasons, months, years?) in a specific site cannot be directly appraised. The archaeological characteristics of sites are related to hominin occupation and faunal assemblages can be biased by the nature of the site (e.g., butchery site, seasonal settlement) or by the origin of the fauna (selective hunting, opportunistic butchery. . .).

At northern sites, records indicate that hominin occupations took place either in dry steppic environments or woodland settings. Some sites yield more reliable environmental data based on multiple proxies such as the British sites (Happisburg 3 and Pakefield), while others are less relevant due to the lack of well-preserved remains (Bytham River sites, Somme Valley sites) (Antoine et al., 2007; Gibbard et al., 2009; Candy et al., 2015). For la Noira (Centre France), hominins disappeared when very cold and dry conditions emerged at the beginning of MIS 16, considered as one of the harshest glacial phases since 1 Ma. This would account for the chronological gap in hominin occupations in the Centre of France and in the Somme Valley between 700 and 500 ka ("bottleneck") up until now (Despriée et al., 2011; Moncel et al., 2020a).

In Southern Europe, if we enlarge the chronological span of the study, Spanish sites suggests recurrent humid and warm environments during occupations but steppic environments are also recorded, for instance at Orce dated to around 1.2 Ma (Rodríguez et al., 2011; Huguet et al., 2013; Rodríguez-Gómez et al., 2014; Rodríguez-Gómez et al., 2016; Blain et al., 2021). At Atapuerca, the early sequences of Sima del Elefante, lower units TE7 to TE16 (Parès et al., 2006; de Lombera-Hermida et al., 2015) were characterised by a humid and warm climate before the cooling recorded from MIS 22 onwards (ca. 900 ka) (Cuenca-Bescós et al., 2011; Blain et al., 2013; Parès et al., 2013). Then the landscape indicates open woodland and steppe correlated with the transitional phase of forest development (possibly correlated with the MIS 22/21 transition) (Rodriguez et al., 2011). The site of La Boella (0.96–0.78 Ma) indicates a mixture of temperate environments (Vallverdú et al., 2014; Mosquera et al., 2015; Mosquera et al., 2016). In Italy and the South of France, dry MIS 16 or 14 environments are associated with occupations, such as Notarchirico, in both MIS 17 and 16, without clear differences in fauna and occupation along lakeshores or water channels (Pereira et al., 2015; Moncel et al., 2020b). This suggests less intense glacial phases in the south compared to the north.

The possibility, that Northwest Europe, including Northern France and Southern England, was at the limit of the "Oekoumen" of *Homo heidelbergenis* of hominins leaving in Europe at that time, especially during the severe MIS 16 glacial event (around 650–620 ka), has be discussed by the scarcity of ocupations. Evidence of occupations during interglacial events or at the transition are more common (see for instance Boxgrove, MIS 13, Souther England; Robert and Parfitt, 1999; Pope, 2002; Leroyer, 2016; Pope et al., 2017). However, some traces of occupations show that hominins could tolerate the environmental conditions and especially cold conditions during glacial events as "permanent residents" or "punctual visitors" (cf. Cohen et al., 2012; MacDonald et al., 2012) and outperform their capabilities and not completely depopulate these territories. Southern climatic data suggest that humidity and temperatures were the two main prerequisites for human occupations (Jouzel et al., 2007; Joannin et al., 2011; Combourieu-Nebout et al., 2015). Pakefield climatic data suggest cold winters but some faunal and plant evidence suggests that low temperatures were possibly rare (Parfitt et al., 2005). To settle these north-western territories, with cold and arid climates, with similar technologies, hominins may possibly have developed specific strategies that cannot be seen in the stone tools. Due to the low quantities of human fossils, no discussions or comparisons of the anatomy of hominins living in Northwest Europe can be undertaken. Indeed, the Mauer mandibule found in Germany merely gives us an idea of the robustness of the hominin living at this latitude (Wagner et al., 2010; Wagner et al., 2011; Fiedler et al., 2019), but we have no idea of the anatomical plasticity of hominins such as *Homo heidelbergensis* during long periods of slow climatic changes (Hosfield and Cole, 2018). de León et al. (2021) show that the brain size of *Homo* enabled him to adapt to various scenarios and environments. So far, there is no evidence of the use of fire and taphonomic processes could have destroyed traces of fire if it existed before MIS 11 (i.e., Ashton et al., 2016; Gowlett, 2016). Faunal remains are not preserved at Moulin Quignon or at la Noira for instance. However, at Notarchirico and Isernia-la-Pineta, the bones do not show any evidence of the use of fire and the scant evidence recorded at the Caune de l'Arago could be due to wind or water transport of micro-charcoals (Deldicque et al., 2021). Seasonal mobility and visits of human groups following migrations of herds and big game could explain the sporadic presence of hominins in these northern regions (i.e., Dennell et al., 2011; Fielder et al., 2019). However, we also have to consider the possibility that hominins could permanently occupy these areas and find strategies to survive in more or less harsh or mild episodes.

Despite footprints suggesting bare feet in some situations and family groups moving in swamps to find food (wet sediments at Happisburgh; Ashton et al., 2014), various solutions can be envisaged to survive winter conditions with clothes (animal skins) and increased energy intakes, ingesting the necessary quantity of food and high nutrition (fat) by extracting animal marrow or collecting plants for instance. Ashton and Lewis, 2012, Ashton, 2015; McDonald et al., 2018, Hosfield et al., 2016 and Hosfield and Cole, 2018 have developed detailed accounts of what was required to survive cold conditions in these latitudes. We also have to bear in mind that hominins could have occupied smaller and specific areas with microclimates, such as sunny parts of valleys or slopes protected from cold winds. Summers (as indicated by the mean temperatures estimated at Happisburgh 3 and Pakefield) may have been warmer than winters with sub-zero temperatures, few available plants and short daylight hours. Food storage could have been practised during winter, facilitated by a diversity of tools, combining light-duty and heavy-duty tools such as bifaces with long functional cutting edges. Moreover, the diversity of the landscape and rich environmental resources (i.e., around Happisburgh and Pakefield) could have been favourable to collecting plants (berries, nuts,. . .) for winter, as well as the large river estuary near the coast (marine and terrestrial resources) (Ashton et al., 2014). Preece and Parfitt, (2012) indicate cut marks on bison bones from Happisburgh (series collected in 1870s). Similar situations may have occurred at Moulin Quignon, located along the Somme Valley close to the confluence with the Scardon River (hot spot for large mammals?), with herds of game, or at la Noira along a tributary of the Loire River. Animal carcasses and plant resources could have been collected to prepare winter. The sites of Notarchirico and Isernia-la-Pineta in Italy confirm that hominins sought out banks of water zones for recovering meat on large herbivore carcasses

(Elephants, bison, horses and cervids) or for hunting (Ben-Dor et al., 2011). At Carpentier Quarry (Antoine et al., 2016), new excavations have revealed that abundant fauna lived there during the deposit of the White Marl (MIS 15) with bovids, cervids, proboscideans, rhinoceros, horse, wild boar, indicating grassland and wooded areas. In Northern France, more than 20 taxa have been recorded during such interglacial phases (Auguste, 2009). Hominins at Moulin Quignon at the glacial/interglacial transition, or possibly during a short cooler event (unrecorded in the sequence), could have discovered this diversity of animals before the onset of cold conditions (Antoine et al., 2019). At Cagny-la-Garenne (Somme Valley, beginning of MIS 12, top of gravels), the fauna was composed of elephants, horses and cervids in a steppe-type landscape (Auguste, 1995; Auguste, 2009; Auguste, 2012).

The hypothesis of a strong relationship during the Middle Pleistocene between hominins and megafauna such as elephants is attractive for explaining the ability to occupy diversified territories even in the northwest (i.e., Reshef and Barkai, 2015; Solodenko et al., 2015; Barkai, 2016). Hominins would have taken advantage of the plentiful carcasses available along water areas with easy primary access and residues and micro-wear traces indicate domestic activities (Hardy et al., 2018; Moncel et al., 2020c). The sequence of the Caune de l'Arago illustrates the possible functional link between bifaces (LCTs) and megafaunal remains (i.e., elephant), during cold events (for instance MIS 14), suggesting that these tools could have been efficient and useful for cutting up large herbivore carcasses (Barsky and Lumley, 2010; Barsky, 2013).

CONCLUSION

In Western Europe, from 700 ka onwards, we sporadically observe new behaviours, such as the possible amplified mobility of human groups, increased selection of raw materials, large and small heavy-duty tools, and curated tools destined for diverse functions, along with some innovations in core technologies. Hominins applied similar strategies and similar evidence of innovations emerges, whatever the environments, indicating adaptation to varied geological, climatic and topographic environments.

European Acheulean assemblages point to strategies with shared basic features, perhaps partly imputed to raw material constraints, activities and diverse traditions, as well as multiple scenarios of dispersals and adaptation to local environments in relation to the climate and extension of territories (Schreve et al., 2015).

Can we describe specific modes of hominin adaptation and cognition to cool or cold climates? The technological data from new fieldwork at Moulin Quignon do not identify original features in Northwest Europe, but rather an ability to adapt behaviour to local and available raw materials, flint nodules, like for the British sites.

Did small groups of hominins in the northwest make short incursions during cooler periods or occupied the area at the onset of a glacial event as at la Noira, leaving the northern region when to cold? We have no evidence of this, but it is likely that small mobile and pioneering groups settled in large territories in Europe and northern latitudes Dennell et al., 2010. This would perhaps indicate higher densities of hominins in Western Europe from 700 ka onwards. This mobility and density of human groups in larger territories raise questions about climatic conditions. The Moulin Quignon series shows that technological behaviours and toolkits are preserved, indicating a complex geographical dispersal of possibly fragmented populations of foragers and collectors in northern areas (cf. Bennett and Provan, 2008; Stewart et al., 2010; Perreault and Brantingham, 2011; Derex et al., 2013; Derex et al., 2016; Andersson and Read, 2014; Kolodny et al., 2015; Grove, 2016; Vaesen et al., 2016; Fogarty and Creanza, 2017; Derex et al., 2018; Fay et al., 2019; Grove, 2019). This does not imply changes in strategies over Western Europe, paleoclimatic data suggesting that hominins appaear to have favoured treeless and open environments in preference to closed forests. New environments did not entail changes in behaviour and we cannot suggest that local extinctions of human groups in unfavourable environments led to decreased cultural diversity or changes in the structure of groups, as we observe the same features among different cultural traditions (cf. Premo and Kuhn, 2010; Kolodny et al., 2015). Who occupied Moulin Quignon and made the bifaes at Barranc de la Boella, la Noira and Notarchirico between 900 and 700 ka? Only Notarchirico yielded a fragment of hominin long bone that is under studied. If the earliest bifaces were made everywhere by what we name *Homo heidelbergensis*, this or possibly these hominins seem to have been more resilient and able to adapt to a higher diversity of climatic and environmental conditions than the earliest populations of hominids in Europe, *Homo antecessor?*

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Article design: M-HM. Initiative of the re-study of the site: AH. Material analyse: M-HM. Writing: M-HM, PA, and J-JB. Editing writing: M-HM, PA, J-JB, DA, and AH. Fieldworks: PA, M-HM, DH, and J-LL. Figures: M-HM, PA, and DH.

FUNDING

The detailed study of the historical, archaeological, anthropological and radiometric data from the Moulin Quignon site, were carried out as part of the ANR (Agence Nationale pour la Recherche) n 2010 BLANC 2006 01, directed by M-HM and Danielle Schreve, focusing on the study of the emergence of bifacial and Acheulean technology in north-western Europe. The analyse has also bee supported by the ANR project n 19-CE27-0011-01 Neandroots. The fieldwork was also supported by the town of Abbeville and the Service regional de l'Archeologie, Hauts de France.

ACKNOWLEDGMENTS

This article, and the detailed study of the historical, archaeological, anthropological and radiometric data from the Moulin Quignon site, were carried out as part of the ANR (Agence Nationale pour la Recherche No. 2010 BLANC 2006 01, directed by M-HM and Danielle Schreve), focusing on the study of the emergence of bifacial and Acheulean Technology in North-Western Europe. The paper has been edited by Louise Byrne, a native English speaker and official translator. We would like to thank the editor and the two reviewers for their really useful comments that enhanced the manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2022.882110/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers | Frontiers in Earth Science

TYPE Original Research
PUBLISHED 25 May 2023
DOI 10.3389/feart.2023.1188663

OPEN ACCESS

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RECEIVED 17 March 2023
ACCEPTED 03 April 2023
PUBLISHED 25 May 2023

CITATION
Ollé A, Lombao D, Asryan L, García-Medrano P, Arroyo A, Fernández-Marchena JL, Yeşilova GC, Cáceres I, Huguet R, López-Polín L, Pineda A, García-Tabernero A, Fidalgo D, Rosas A, Saladié P and Vallverdú J (2023), The earliest European Acheulean: new insights into the large shaped tools from the late Early Pleistocene site of Barranc de la Boella (Tarragona, Spain). *Front. Earth Sci.* 11:1188663. doi: 10.3389/feart.2023.1188663

The earliest European Acheulean: new insights into the large shaped tools from the late Early Pleistocene site of Barranc de la Boella (Tarragona, Spain)

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Since the oldest known Acheulean lithic techno-typological features in Europe were reported at the site of Barranc de la Boella (Tarragona, Spain), continuous fieldwork has been conducted there in archeological deposits of the late Early Pleistocene age (0.99–0.78 Ma). As a result, excavations in two of the three open-air localities have significantly expanded the collection of lithic and faunal remains, allowing us to make progress in the interpretation of the hominin behaviors in an open-air fluvial-deltaic sedimentary environment. This includes examples of cumulative palimpsests, such as those found at the locality of La Mina, in which hominins only had a minimal role as modifying agents, as well as the extraordinary mammoth butchery site recorded at the Pit 1 locality. The aim of this paper is to present a comprehensive update of the collection of large shaped tools and to assess its significance in the framework of the earliest occurrence of the Acheulean in Europe. This cultural entity is increasingly well-documented for the early Middle Pleistocene, but very little is known about its presence in Europe before the Brunhes–Matuyama boundary. Large shaped tools appear in the three localities explored in the Unit II of Barranc de la Boella, including choppers (unifacial and bifacial) and standard Acheulean forms, such as picks, knives, and cleaver-like forms. Techno-typological and morphometrical analyses revealed a basic heavy-duty component obtained through simple shaping sequences coupled with significantly more elaborate tools produced on various large blanks (cobbles, slabs, or flakes). The complete bifacial and bilateral shapings have yet to be documented, but the present specific tool assemblage attests to the Early Acheulean technological threshold. Hence, the archaeological data from

Barranc de la Boella provide insights into the first appearance of the Acheulean technology in Europe and add critical information to the debate on the technological variability of the Early Pleistocene hominin occupation of the continent. The results of this study revealed a technological assemblage unique in the known late Early Pleistocene archeological record from Europe, different from the rest of ancient Acheulean sites in this continent, which are dated at the Middle Pleistocene. This lends support to the hypothesis that Barranc de la Boella may represent a previously unrecognized Early Acheulean dispersion out of Africa connected to its first evidence at the gates of Eurasia, potentially moving over the northern Mediterranean coastal road to reach Western Europe.

KEYWORDS

Early Acheulean, large shaped tool, trihedral pick, early Europeans, Barranc de la Boella

1 Introduction

Much is known about the appearance of the Acheulean in Africa around 1.75 Ma ago, or even ~1.98 Ma according to estimation models (Key et al., 2021), and about its quick expansion throughout the continent (Lepre et al., 2011; Beyene et al., 2013; de la Torre, 2016; de la Torre et al., 2018a; Kuman, 2019, and references therein). There is general agreement about its significance in terms of technological complexity and its related behavioral and cognitive implications for the genus *Homo*. It has been considered the most significant technological development in the Early Stone Age and a threshold in technological, behavioral, and cognitive evolution (e.g., Sharon, 2007; Lycett and Gowlett, 2008; de la Torre and Mora, 2014; Carbonell et al., 2016; de la Torre, 2016; Wynn and Gowlett, 2017; Gowlett, 2020).

The Acheulean is reflected in the archaeological record as a set of widely accepted defining technological features (and further defining "Mode 2" technology; Clark, 1968). These include the advent of the so-called large cutting tools (LCT), which involve large blank production, progress in raw material management, shape standardization, and distinctive and recognizable tool types (handaxes, cleavers, picks, knives, etc.) that appear to have occasionally served as mobile toolkit elements. These characteristic Acheulean tools are accompanied by improved core reduction (i.e., knapping strategies) for medium and small products (e.g., Keeley, 1993; Clark, 1994; de la Torre, 2011; de la Torre, 2016).

However, there is more uncertainty about Early Acheulean occurrences outside of Africa. The currently accepted scenario is that it presented around 1.5/1.4 Ma ago in the Levant ('Ubeidiya; Bar-Yosef and Goren-Inbar, 1993) and India (Attirampakkam; Pappu et al., 2011). Surprisingly, there is a lack of such early evidence in Western Europe, and no conclusive explanations for this absence are currently available. This could simply reflect a research gap, but it is also proposed that possible environmental or paleoecological barriers prevented the Early Acheulean from spreading to a part of the European continent where communities practicing Mode 1 technology were quite well-established (Carbonell et al., 2008; Carbonell et al., 2010; Moncel, 2010; Parfitt et al., 2010; MacDonald and Roebroeks, 2012; Mosquera et al., 2013; Barsky et al., 2016; Despriée et al., 2018, and references therein).

The earliest Acheulean occurrence in Europe has been the subject of extensive inquiry in recent years, based on both new archaeological sites and updates on previously recognized locations. An Acheulean presence earlier than the formerly accepted dates for its first appearances from MIS 13 (Moncel et al., 2015; Moncel et al., 2018, Moncel and Ashton, 2018) has been documented at early Middle Pleistocene sites such as Bois de Riquet (US4) (Bourguignon et al., 2016; Viallet et al., 2022), La Noira (Moncel et al., 2013; Moncel et al., 2021; García-Medrano et al., 2022), Moulin Quignon (Antoine et al., 2019; Moncel et al., 2022) in France, Notarchirico in Italy (Piperno, 1999; Moncel et al., 2020b), and Brandon Fields and Fordwich in the United Kingdom (Davis et al., 2021; Key et al., 2022).

In 2014, we published the first findings from the late Early Pleistocene open-air site of Barranc de la Boella (Tarragona, Spain; Vallverdú et al., 2014a). We presented geological, faunal, and lithic data from the same stratigraphic Unit II at three different excavated localities. The evidence, dated to 0.99–0.78 Ma, included traces of hominin activity in a rich fluvial-deltaic ecosystem, including a single butchery event of one mammoth (*Mammuthus meridionalis*) carcass (Pit 1), as well as more sparse associations of stone tools and anthropogenic bone breakage at other localities (La Mina and El Forn). Among the stone tool collection dominated by cores and flakes, we reported isolated large cutting tools (a pick and a cleaver-like tool) that, combined with some features of the knapping methods, lead us to support an Acheulean designation (Vallverdú et al., 2014b; Mosquera et al., 2015).

Furthermore, the set of technological features observed in the Barranc de la Boella Unit II collection prompted our claim for the existence of Early Acheulean technology in Europe (Mosquera et al., 2016). By that time, Bose and other Chinese (Hou et al., 2000; Li et al., 2014) sites had demonstrated that Acheulean tool forms (because of either dispersal or convergence phenomena) were present in East Asia by the late Early Pleistocene, and the new dating of Attirampakkam in India (Pappu et al., 2011) showed that they appeared in South Asia much earlier than previously thought. In this context, the evidence at Barranc de la Boella could well be mirroring the situation in Western Europe, where the uncontested Acheulean presence was fully accepted only for the Middle Pleistocene.

Our hypothesis about the presence of the Acheulean in Western Europe during the late Early Pleistocene was initially supported by qualitatively significant but quantitatively scarce evidence, which led to unequal acceptance among colleagues and a general requirement for more diagnostic elements (Moncel et al., 2015; Moncel et al., 2020a; Moncel et al., 2020b; Méndez-Quintas et al., 2018). To address this challenge, based on the proven richness of Unit II at Barranc de la Boella in three discrete localities, we decided in 2016 to significantly enlarge the excavated surface area at two of them: Pit 1 and La Mina. Even though the excavation work has only partially reached the targeted layers, and detailed study of the excavated materials is still in progress, the time is ripe for a first update on the current collection of large shaped tools recovered so far.

In this article, we provide new data on a sample of artifacts that help us to technologically characterize the assemblage. These are the large shaped tools, including the groups of heavy-duty tools and large cutting tools (*sensu* Isaac, 1977), as well as a few but characteristic large flakes (>100 mm). These data allow us to back up our previous interpretations and support our original claim of Early Acheulean evidence in Western Europe around 1 Ma ago.

We are aware that such evidence is so far scarce for that time period and geographical area, as other supposedly Iberian examples of this early presence of the Acheulean techno-complex are based on still limited information and debatable interpretations (Scott and Gibert, 2009; Walker et al., 2020). Consequently, the uniqueness of Barranc de la Boella justifies the need for this update. In the current scenario involving a small number of sites that represent little more than isolated snapshots of hominin occupation (Moncel et al., 2018), any robust input can be crucial for valuable reconstructions (Key and Ashton, 2022).

Thus, Barranc de la Boella contributes relevant data for reconstructing the first phases of hominin settlement in Western Europe. In technological terms, it could shed light on the apparent technological gap between the earliest (Mode 1) and later Acheulean hominin populations, as well as provide clues to addressing wider technological questions, such as the origin of the Acheulean in Europe in terms of local evolution (innovation), out-of-Africa dispersal events, and convergence phenomena.

2 The site of Barranc de la Boella

The Barranc de la Boella (La Canonja, Spain) is located 7 km northwest of the city of Tarragona, on the north-eastern Iberian Peninsula. Geomorphological and paleoenvironmental interpretations have suggested the site was situated within a fluvial-deltaic environment, with braided-channel and pool deposits, associated with the terrace T + 60 m of the lower Francolí River basin, c. 50 m above the Mediterranean Sea level. Its 9-m-thick stratigraphic succession was formed from the late Early to the Upper Pleistocene. The deposit is quite continuous along the explored area and is currently dissected by a modern seasonal ravine.

Despite being known since c.1930, Barranc de la Boella was only published as a paleontological site in 1973 (Vilaseca, 1973), and the first systematic excavations were only conducted in 2007 (Saladié et al., 2009; Vallverdú et al., 2009). The results derived from the first field seasons have been internationally known since 2014 when general works (Vallverdú et al., 2014a; Vallverdú et al., 2014b), as well as specific studies on biochronology (Lozano-Fernández et al., 2013; Lozano-Fernández et al., 2014) and on taphonomy and zooarchaeology (Pineda et al., 2015, Pineda et al., 2017a; Pineda et al., 2017b; Rosas et al., 2015), were published. Paleomagnetic, cosmogenic, and biochronological data provided in these studies situated the richest basal strata, grouped in Unit II, in the late Early Pleistocene (from 0.99 to 0.78 Ma).

Research carried out during the first few years in Unit II revealed a rich archaeological landscape scattered with witnesses of hominin and animal activity, which were identified in several stratigraphic profiles, in isolated surface and stratified findings, and in three excavated localities: Pit 1 (or Cala 1), La Mina (Pit 2), and El Forn (Pit 3) (Figure 1). These testimonies included evidence of co-occurrence between the hominins and other carnivores in a context of high competition between the different predators' paleo guilds (Pineda et al., 2017b).

At Pit 1, a surface of 12 m^2 was excavated in 2007. In the uppermost fertile layer of Unit II (level 2), we described a single animal butchery site (according to Isaac, 1978), including a partial carcass of a prime adult *M. meridionalis* with possible cut marks on ribs as well as abundant notches and bone fractures produced by other mammoths trampling. Such fossil remains were associated with a rich scatter of stone tools around them. The lithic assemblage primarily consisted of local chert that had been knapped, used, and discarded *in situ*, as evidenced by many refitting groups and butchery use-wear traces, aside from some percussive material made of other raw materials. Relevantly, there was a well-shaped schist trihedral pick with that assemblage, whose blank was probably a split cobble (Mosquera et al., 2015).

At La Mina, excavations conducted since 2010 have extended the former 6 m^2 pit, opened in 2008, to a 35 m^2 area. This locality turned out to be the richest in the Barranc de la Boella in terms of faunal remains, both in the number of specimens and in taxonomic diversity, especially for level 2 of Unit II (Pineda et al., 2017b). Although anthropogenic fracturing has been identified, no cut marks have been found to date. This is likely due to the poor preservation of the surface of the bones because of the erosion caused by the sandy sediment. The abundance of signals from large carnivores is coupled with the presence of coprolites throughout the whole deposit (Pineda et al., 2015; Pineda et al., 2017a; Pineda et al., 2017b). The enclave is interpreted as a loitering location for hominins and carnivores to acquire resources, likely because of the area's high concentration of prey. The formerly published lithic assemblage for Unit II consisted of only 80 artifacts, including varied percussive material on different raw materials, some cores and small products of chert, and a small but significant group of choppers, but an absence of LCTs (Mosquera et al., 2016).

Finally, only 15 m opposite Pit 1, there is the El Forn locality, where the 40 m^2 pit excavated between 2008 and 2013 brought to light three archaeological levels inside the geological Unit II. This locality has the lowest density and the greatest dispersion of remains, as only levels 2 and 3 present a significant scatter of materials. The lithic assemblage at El Forn has similarities to the one found at La Mina, with the exception of the presence of a second LCT of schist, which was a cleaver-like tool (Mosquera et al., 2016).

The presence of certain large shaped tools (the pick and the cleaver) led us to tentatively identify Barranc de la Boella as the earliest evidence of the Acheulean technology in Western Europe (Vallverdú et al., 2014a) and fostered the first comprehensive study of the stone tool collection recovered up to the 2013 season (Mosquera et al., 2016).

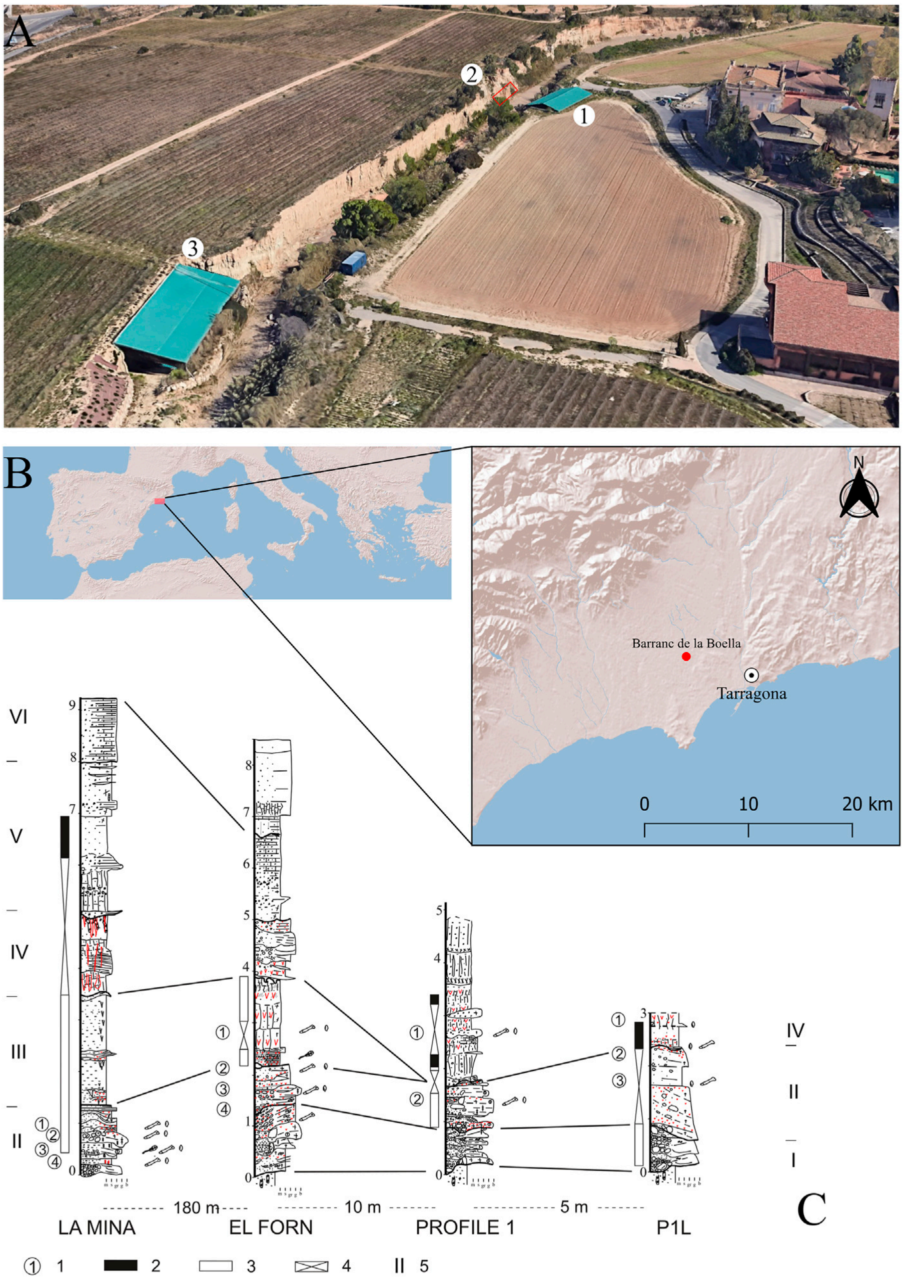

FIGURE 1
Location map and stratigraphy of Barranc de la Boella. **(A)** General view of the sites with the modern ravine cutting the sedimentary succession and the three localities: 1. Pit 1, 2. El Forn, and 3. La Mina; **(B)** Location map of the site in the western Mediterranean basin and in the Camp de Tarragona area; **(C)** Lithostratigraphic logs of the Barranc de la Boella localities: La Mina, El Forn, and Pit 1 (Profile 1 and P1L); (modified from Vallverdú et al., 2014a). Legend: 1. Archaeopaleontological level, 2. Reverse magnetic polarity, 3. Normal magnetic polarity, 4. Undetermined magnetic polarity, and 5. Litostratigraphic units.

As the results of our first period of fieldwork started to be echoed by the scientific community, an unequal acceptance of our claimed Acheulean evidence emerged (Rolland, 2013; Moncel et al., 2015; Moncel et al., 2016; Moncel et al., 2018; Moncel et al., 2020a; Moncel et al., 2020b; Bourguignon et al., 2016; Méndez-Quintas et al., 2018; Muttoni et al., 2018; Rosell and Blasco, 2021; Haynes, 2022; Viallet et al., 2022), demonstrating the importance of the site and, at the same time, that more substantiation was needed to properly assess its significance in the context of Western Europe. Accordingly, the research team decided to actively increase the evidence by excavating extensive areas in some of the known archaeological deposits. These displayed the typical irregularity and discontinuity found in open-air sites in fluvial environments. Therefore, it was considered necessary to excavate broad surfaces in an effort to develop the most comprehensive record possible. In 2016, after conditioning the Pit 1 and La Mina sites with due-protective roofs,

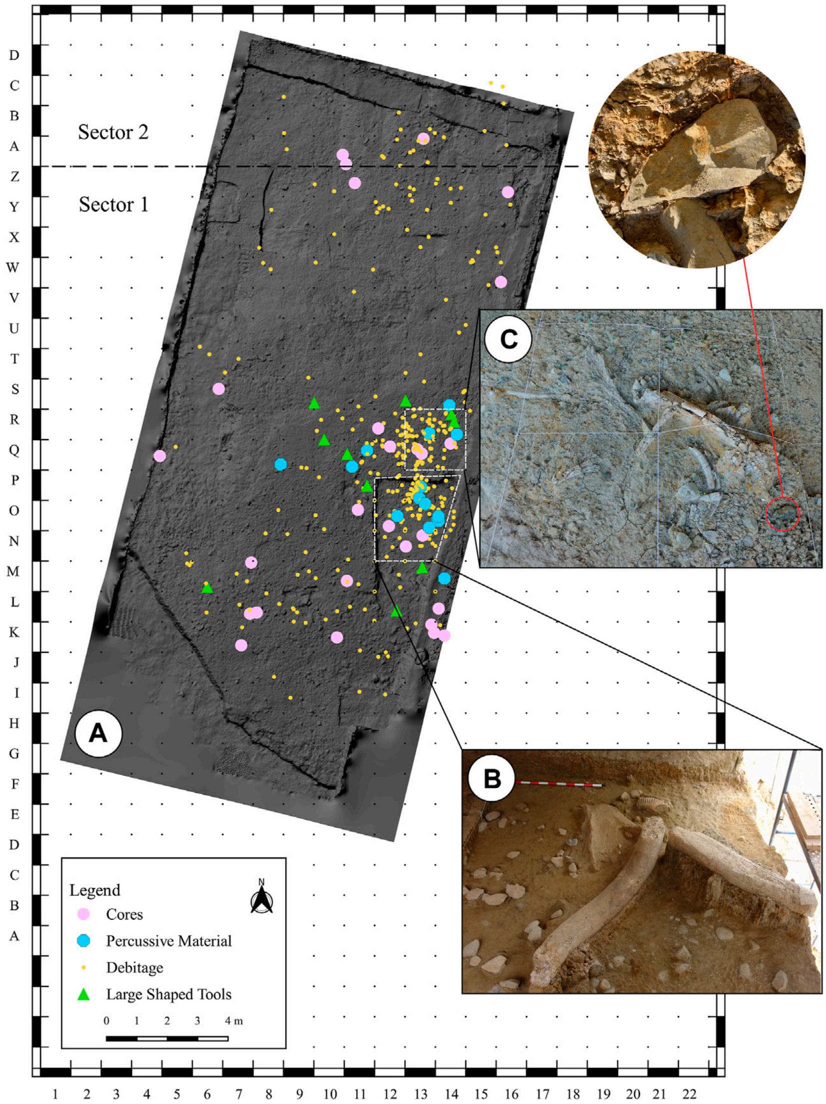

FIGURE 2
(A) Ongoing excavation at Pit 1, with a photogrammetric reconstruction of the excavated surface and the plot of the lithic artifacts recovered up to the 2022 season; **(B)** image of the mammoth remains and associated elements at the 2007 test-pit; and **(C)** image of the mammoth remains and associated elements uncovered in the 2018 season, among which is a schist pick (ref. C1-2018-S1-II-2-R14-9).

two considerable areas were obtained for extension excavation (210 and 250 m^2, respectively) (Supplementary Figures S1, S2).

In 2018 at Pit 1, we reached the layer where we discovered the mammoth carcass in 2007, and since then, we have concentrated on following that paleosurface. Currently, there is a surface of c. 190 m^2 of sediments from Unit II in the process of excavation (Figure 2). Following the mammoth tusks, molars, and scapula from 2007, the newly excavated area has revealed several ribs and a femur from the same individual. Associated with the fauna, there was an exceptional accumulation of chert tools, including cores, flakes, very few retouched flakes (mainly denticulates), and abundant debris. The presence of *in situ* knapping activities was corroborated by representative lithic categories and refitting sets that were directly visible during the excavation process. Significantly, the large-tool component, almost exclusively made of schist, has increased with five picks, one knife, one cleaver, and two choppers. Although the excavation has not completely uncovered the wavy paleo-surface of the archaeological layer across the whole explored area, the plot of the materials recovered so far clearly shows a concentration of materials around the mammoth carcass, and a progressive decrease in density away from it. This distribution also affects the presence of large shaped tools. To the north of the locality, another concentration of remains appears to be drawn; for the moment, it is not possible to establish the possible relationships between them (Figure 2).

At La Mina, the excavation of Unit II is currently covering a surface of approximately 180 m^2. According to the initial survey (4 m^2), Unit II contains at least five archaeological levels, of which only levels 1 to 4 have so far been significantly explored (35 m^2 up to 2016). To date, only level 1 has been fully excavated, and extensive excavation of level 2 has begun. Level 2 is the richest one in terms of faunal and lithic remains. Additionally, Level 3 also stands out from the rest of the succession due to a significant accumulation of hyena coprolites, which could be interpreted as a place these animals used as a latrine (Pineda et al., 2017a). At Unit II of this locality, the original large-tool component was formed by only four choppers (two of them bifacial). New excavations not only quantitatively increased the sample by incorporating three new elements for that group but also contributed qualitatively with a knife and two picks.

In parallel to the enlarged fieldwork, studies have intensively continued, not only regarding specific technological aspects such as the reduction strategies (Lombao, 2021) but especially in terms of paleontological and biochronological research (Lozano-Fernández et al., 2019; Madurell-Malapeira et al., 2019; Fidalgo et al., 2023a; Fidalgo et al., 2023b), as well as in taphonomical and zooarchaeological subjects (Pineda et al., 2014; Pineda et al., 2017b; Pineda et al., 2019; Pineda and Saladié, 2022). In this sense, the paleontological record currently available for Barranc de la Boella Unit II reflects a resource-rich area where competition between carnivores and hominins for prey and utilization of carcasses was at times high. Along with stone tools, abundant and taxonomically varied faunal remains have been recovered; megaherbivores (*M. meridionalis* and *Hippopotamus antiquus*) are the dominant taxa, but the site also yielded other ungulates (*Stephanorhinus hundsheimensis*, *Equus altidens*, *Megacerini* indet., *Cervus elaphus*, *Dama vallonnetensis*, *Capreolus* sp., *Bison schoetensacki*, and *Sus strozzi*), rodents (*Castor fiber*), and carnivores (*Ursus deningeri*, *Canis mosbachensis*, *Panthera* sp. of large size, *Lynx pardinus*, and *Panthera gombaszoegensis*) (Vallverdú et al., 2014a; Pineda et al., 2017b; Madurell-Malapeira et al., 2019; Fidalgo et al., 2023a; Fidalgo et al., 2023b) (Supplementary Table S1). Despite their abundant coprolites, as well as tooth-marked and digested bones, there are as yet no hyena remains (Pineda et al., 2017a).

The specific diversity of these deposits is the reflection of a varied biotope with large bodies of water, in which primary and secondary consumers concurred. In terms of bone surface preservation, leaching effects causing a loss of mass have been identified, especially in some of the Pit 1 remains. At the La Mina locality, a slight abrasion has been documented on the bones in the form of striations caused by trampling within the sandy sediments of the deposit. Weathering is the most frequent modification at El Forn, mainly corresponding to Behrensmeyer's (1978) stage 1 but also higher (Vallverdú et al., 2014a; Mosquera et al., 2015; Pineda et al., 2017b). The anatomical profiles in relation to the bones recovered and their portions (epiphysis vs. diaphysis), such as the complete bones vs. fragmented bones, indicate a high degree of competition for consumption in La Mina (level 2), in which the activity of both hominins (stone tools) and carnivores (tooth marks and other modifications) seems to be high. At El Forn, where the activity of these agents seems to be less intense, levels of competition are low-to-moderate. To sum up, the La Mina and El Forn localities are the outcome of hot spots of activity in open-air ecological systems that tend to give rise to assemblages in which different actors have contributed to their formation without the existence of a dominant agent or process. This is not the case for Pit 1, where a high-resolution event of the butchery exploitation of a large mammoth body has been revealed.

3 Materials and methods

This study analyzes the whole lithic assemblage of Unit II from Barranc de la Boella updated to the 2022 fieldwork season, which amounts to 966 elements. Table 1 compiles aggregate data on assemblage composition by raw materials, technological groups, and localities. However, the numbers provided cannot be taken as definitive because most of the levels of Unit II are still being actively excavated.

For Pit 1, we included the materials from level 2 at Unit II (n = 427), which has a high archaeo-stratigraphic uniformity. Additionally, we have also included a schist cleaver recovered when building the protection structure; it is highly likely that this artifact comes from Unit II.

Excavation in the La Mina locality has so far revealed less dense archaeological concentrations, and some of the five levels distinguished in the previous test pits have not been reached by the ongoing works. For this reason, as in previous studies (Mosquera et al., 2016), we decided to keep all the materials for Unit II together (n = 435).

So far, El Forn is the only locality in which the excavation has concluded. As in Mosquera and colleagues (2016), we have grouped all the materials from Unit II, including levels 2, 3, and 4 (n = 103). The small differences identified during this study with respect to what was published may be due to specific technological or stratigraphical reassessment of some elements.

In all cases, natural elements such as cobbles or pebbles with no trace of anthropic activity were excluded, even for those that were initially recorded and collected. In such a fluvial environment, the recognition of elements as simply manuports is difficult to assess in the absence of any anthropic signal. Also, except for the cleaver mentioned for Pit 1, surface materials were not considered.

To properly frame the group of large shaped tools studied here, Table 1 shows the distribution of the currently available sample at Unit II. The technological categories considered were as follows: elements related to percussive material (cobbles and broken cobbles with fractures and battering traces on their ends), cores, flakes (including the whole ones classified according to size, the broken flakes, and the flake fragments and angular fragments counted together), small shaped tools, and large shaped tools. Although most of the large shaped tools are longer than 100 mm, we include ten artefacts in this group ranging from 70 to 100 mm in length, all of them on cobble blanks, because they represent characteristic macro-tool types such as choppers (unifacial and bifacial). In the same way, we include in the group of small shaped tools five retouched flakes bigger than 70 mm, as they are simple denticulates. The metrical distribution of the different technological categories by localities can be consulted in Supplementary Tables S2–S4.

Despite the variety of raw materials, chert is predominant (87.4% for Pit 1, 78.6% for El Forn, and 87.8% for La Mina). In all cases, this material shows simple core and flake reduction sequences, which are specially complete at Pit 1 regarding technological components and flaking phases. The typological variability of small chert tools is very reduced, with a dominance of denticulates (77.3%) and scrapers (12.2%) over other marginally represented types. Complementary materials are schist (P1: 6.6%, EF: 13.6%, LM: 4.8%), quartz (P1: 3%, EF: 3.9%, LM: 2.7%), and

TABLE 1 Lithic assemblage of Barranc de la Boella Unit II. Distribution of main technological groups by raw materials for the three different localities. (*) One piece without secure stratigraphical context has been included; % (1) considered for the collection of each locality, % (2) considered for the whole assemblage.

LOCALITY/Raw material	Percussive material	Cores	Flakes						Small-shaped	Large-shaped	Total	
			<20 mm	21–60 mm	61–100 mm	>100 mm	Broken	F. F. & frags				% (1)
PIT 1	**15**	**28**	**56**	**122**	**9**	**1**	**67**	**97**	**22**	**11**	**428**	
Schist	4	1		6		1	1	5		10(*)	**28**	*6.54*
Granite	3										**3**	*0.70*
Sandstone	4	1									**5**	*1.17*
Lydite	2										**2**	*0.47*
Quartz			3	2				8			**13**	*3.04*
Quartzite	2			1							**3**	*0.70*
Chert		26	53	113	9		66	84	22	1	**374**	*87.38*
EL FORN	**10**	**8**	**9**	**35**	**2**		**9**	**16**	**7**	**7**	**103**	
Schist	7						1		1	5	**14**	*13.59*
Granite										1	**1**	*0.97*
Sandstone	1										**1**	*0.97*
Quartz	1	1						2			**4**	*3.88*
Quartzite	1									1	**2**	*1.94*
Chert		7	9	35	2		8	14	6		**81**	*78.64*
LA MINA	**20**	**22**	**53**	**103**	**6**	**1**	**51**	**133**	**37**	**10**	**435**	
Limestone				1						1	**2**	*0.46*
Schist	7			2		1	1	2	3	5	**21**	*4.83*
Granite	4	1									**5**	*1.15*
Sandstone	4								1		**5**	*1.15*
Porphyry	1									1	**2**	*0.46*
Quartz	2		1	4				5			**12**	*2.76*
Quartzite	2	1		1			1			1	**6**	*1.38*
Chert		19	52	95	6		49	126	33	2	**382**	*87.82*
TOTAL UII	**45**	**57**	**118**	**260**	**17**	**2**	**127**	**246**	**66**	**28**	**966**	
% (2)	*4.66*	*5.09*	*12.22*	*26.92*	*1.76*	*0.21*	*13.15*	*25.47*	*6.83*	*2.9*		

TABLE 2 List of large shaped tools and flakes >100 m of Barranc de la Boella Unit II, localities Pit 1, El Forn, and La Mina; (*) marks an artifact without clear stratigraphic correlation with the other pieces at Pit 1.

Reference	Material	Blank	Measure (mm)			Weight (gr)	Volume (cm^3)	Tool type
Pit 1								
C1-2019-S1-II-2-Q11-5	Schist	Cobble	157	83	39	630	226.07	Chopper (distal)
C1-2021-S1-II-2-S13-2	Schist	Cobble	91	62	18	141	54.84	Chopper (distal)
C1-2018-S1-II-2-R14-9	Schist	Cobble	164	73	85	1065	366.28	Pick
C1-2019-S1-II-2-R10-5	Schist	Cobble	164	65	49	655	247.61	Pick
C1-2019-S1-II-2-S10-2	Schist	Cobble	151	115	72	1304	507.72	Pick
C1-2019-S1-II-2-P11-1	Schist	Unknown	136	94	73	740	316.11	Pick
C1-2007-S1-II-2-M13-7	Schist	Flake	161	85	58	682	245.54	Pick (pick-like handaxe)
C1-2020-S1-II-2-M06-2	Chert	Block (slab)	139	86	41	632	243.35	Pick
C1-2018-S1-II-2-R14-12	Schist	Flake	112	92	44	532	216.93	Knife
C1-2013-Surf-1*	Schist	Flake	137	117	36	687	253.25	Cleaver (cleaver-like)
C1-2021-S1-II-2-L12-7	Schist	Cobble	96	96	25	331	124.64	Indeterminate
C1-2019-S1-II-2-T06-2	Schist	Flake	109	191	44	1162	428.64	Large flake (retouched)
El Forn								
EF-2011-II-3-J11-2	Schist	Cobble	214	132	65	2620	972.03	Chopper (lateral)
EF-2013-II-3-C11-1	Schist	Cobble	125	90	39	585	225.34	Chopper (lateral-distal)
EF-2011-II-2-I14-2	Granite	Cobble	95	64	30	234	91.88	Chopper (pointed)
EF-2013-II-2-H13-3	Quartzite	Cobble	85	55	50	309	117.35	Bifacial chopper (distal)
EF-2009-II-2-N14-4	Schist	Flake	153	118	48	960	344.99	Cleaver (cleaver-like)
EF-2012-II-4-H12-1	Schist	Cobble	140	123	25	498	188.99	Indeterminate
EF-2012-II-4-K13-4	Schist	Cobble	141	71	43	560	220.78	Indeterminate
La Mina								
LM-2013-S1-II-2-W13-1	Schist	Cobble	90	78	43	253	106.63	Chopper (pointed)
LM-2019-S1-II-1-V12-3	Schist	Cobble	108	90	55	585	219.54	Chopper (distal)
LM-2010-S1-II-2-Y14-8	Schist	Cobble	95	72	32	276	117.12	Chopper (lateral-distal)
LM-2010-S1-II-1-O15-1	Porphyry	Cobble	145	100	55	966	377.04	Bifacial chopper (lateral-distal)
LM-2013-S1-II-2-U13-1	Quartzite	Cobble	75	73	51	356	136.63	Bifacial chopper (distal)
LM-2021-S2-II-2-B18-1	Limestone	Cobble	72	64	45	272	102.38	Bifacial chopper (distal)
LM-2021-S2-II-2-F14-1	Chert	Cobble	92	58	31	188	76.63	Bifacial chopper (lateral)
LM-2022-S2-II-2-A13-1	Schist	Cobble	220	115	76	2438	888.25	Pick
LM-2022-S2-II-2-A16-4	Chert	Cobble	117	81	78	967	374.66	Pick
LM-2014-S1-II-2-X15-7	Schist	Flake	166	108	40	881	359.78	Knife
LM-2020-S1-II-1-W16-3	Schist	Flake	107	143	51	1255	482.67	Large flake

quartzite (P1: 0.7%, EF: 1.9%, LM: 1.4%). Among these, schist and quartzite stand out, as they were used mainly for production of large shaped tools. Other rocks are represented by very few elements and without any visible selection pattern, such as granite (P1: 0.7%, EF: 1%, LM: 1.1%), sandstone (P1: 1.2%, EF: 1%), lydite (P1: 0.5%), limestone (LM: 0.5%), and porphyry (LM: 0.5%). Given its importance in the assemblage, it is worth noting that the group of schist includes a sandy one, sometimes with marked schistosity plains, and others that are very fine-grained and compact, with the appearance of hornfels. All these varieties of raw materials and the observed blank formats are locally available around the immediate alluvial environment (Mosquera et al., 2016). The Quaternary deposits on which the fluvial-deltaic formation developed worked as secondary outcrops, offering metamorphic (schists and quartzite), igneous (granite and dioritic porphyry), sedimentary materials (chert, limestone, and lydite), and vein quartz, in the form of pebbles and cobbles with a high metrical range, that were more or less rolled and globular depending on the nature and distance of the primary outcrops from which they were derived.

As mentioned previously, this study specifically focuses on the large shaped tool components, made on any type of blank (core tools and retouched large flakes) (n = 28). Additional attention is paid to the large flakes (>100 mm, n = 2). To provide a comprehensive description of this collection, we performed technological analysis using the logic analytic system following other recent papers (e.g., Ollé et al., 2013; de Lombera-Hermida et al., 2020), which was complemented with different techno-typological, volumetric, and geometric morphometrical analyses (Lombao et al., 2020; Lombao et al., 2022; García-Medrano et al., 2022; García-Medrano et al., 2023). Detailed graphic information is provided by means of systematic photography and 3D scanning with diacritic interpretation. All the tools were photographed using a Nikon D600 digital camera (AF-S DX Micro NIKKOR 40 mm lens) and scanned using the Artec Space Spider 3DScan (Artec Studio v15 software) and the Breuckmann smartSCAN3D-HE Scanner with a 250-mm field of view (Breuckmann Optocat 2012 R2-2206 software).

Regarding the functional analysis of the large shaped tools from Barranc de la Boella, a residue and microwear study has been launched following a multi-technique approach that combines reflected light, 3D digital, and scanning electron microscopy (Martín-Viveros and Ollé, 2020). To date, only very preliminary results are available, which come from screening under the digital (Hirox KH-8700) and the scanning electron (ESEM FEI Quanta 600) microscopes to assess the preservation of the materials, to describe some of the observed macrotraces, and to explore the existence of preserved residues.

As a detailed discussion of typological terminology is beyond the scope of this paper, we refer to the large shaped tools (*sensu* Kleindienst, 1962) using commonly accepted terms for Lower Paleolithic simple forms, such as choppers, as well as typical Acheulean forms such as bifacial handaxes, cleavers, picks, or knives (e.g., Bordes, 1961; Kleindienst, 1962; Leakey, 1971; Isaac, 1977; Schick and Toth, 1993; Chavaillon and Piperno, 2004; Sharon, 2007). Regarding the choppers, we adopted terminological proposals that consider them as a whole (e.g., Kleindienst, 1962; Leakey, 1971; Isaac, 1977; Schick and Toth, 1993; Chavaillon and Piperno, 2004), using "bifacial chopper" to refer to tools with two faces flaked, rather than its equivalent "chopping tool" (e.g., Movius, 1948; Bordes, 1961).

Additionally, we applied 3D geometric morphometrics to analyze tool shape variation. The 3D models were processed using AGMT3-D software v.3.1 (Herzlinger and Grosman, 2018; Herzlinger and Goren-Inbar, 2020). This consists of a data-acquisition procedure for automatically positioning 3D models in space and fitting them with grids of 3D semi-landmarks. Each point of the grid consists of two semi-landmarks, one placed on each face of the artifact, so that a 50 × 50 grid provides 5,000 landmarks. The multivariate outline data were projected in two dimensions so that the underlying shape variables could be qualitatively examined and compared. To interpret the principal component analysis (PCA) results from a morphological perspective, Procrustes superimposed shape data were examined using thin-plate splines to facilitate the visualization of shape changes from the group mean along relative warp (i.e., the principal component; PC) axes. By examining the morphological deformations and XY plots of specimens from the PCA scatters, it is possible to interpret shape variation by itself and compare the different tools within a site or between different sites. In addition, the derived principal component scores also allow the application of other quantitative tests of multivariate equality of means between the groups (Costa, 2010; Herzlinger and Grosman, 2018; Herzlinger and Goren-Inbar, 2020). Specific multivariate analysis of variance (MANOVA) of the first 10 PCs helps to evaluate whether there are statistically significant differences between multiple groups. The alpha level for significance was determined as $p < 0.05$.

The landmark data were used to calculate the degree of deviation from perfect bilateral and bifacial symmetries, as well as the edge section regularity of each item in the sample (Herzlinger and Goren-Inbar, 2020). The bilateral symmetry analysis was conducted by measuring the mean 3D Euclidean distance between a mirror reflection of the landmarks placed on one lateral half of each tool and the corresponding landmarks on the other half. The same procedure was performed for bifacial symmetry but on the two opposing faces. In a perfect bilaterally or bifacially symmetrical tool, the value of these indices is 0, with increasing values indicating less symmetrical tools.

4 Results

Table 1 displays the relative weight of the large shaped tools group according to localities and raw materials. Table 2 shows their detailed distribution and summarizes their main technological features. In this section, we pay attention to the techno-typological, metric, volumetric, and morphometrical characteristics recorded at Barranc de la Boella Unit II as a whole, while providing a comprehensive graphic illustration of the more representative artifacts (Figures 3–11). A detailed description of technical attributes and shaping processes piece by piece is provided in Supplementary Table S5, together with additional graphical documentation (Supplementary Figures S3–S10). Because of the reduced sample, the 3D geometric morphometric analysis has been carried out with all the Unit II materials taken together.

4.1 Techno-typological features of the large shaped tool assemblage

The collection at Pit 1 consists of 11 large shaped tools and one large flake, including two choppers, six picks, one cleaver, one knife, and one typologically indeterminate element (Table 2). There is uniformity in raw materials, as all are made of schist, except for one of the picks, which is made of chert. The two choppers are distally shaped. The first was made on an elongated cobble with an apparent oblique fracture (Figure 3B). The second one was made on a flat,

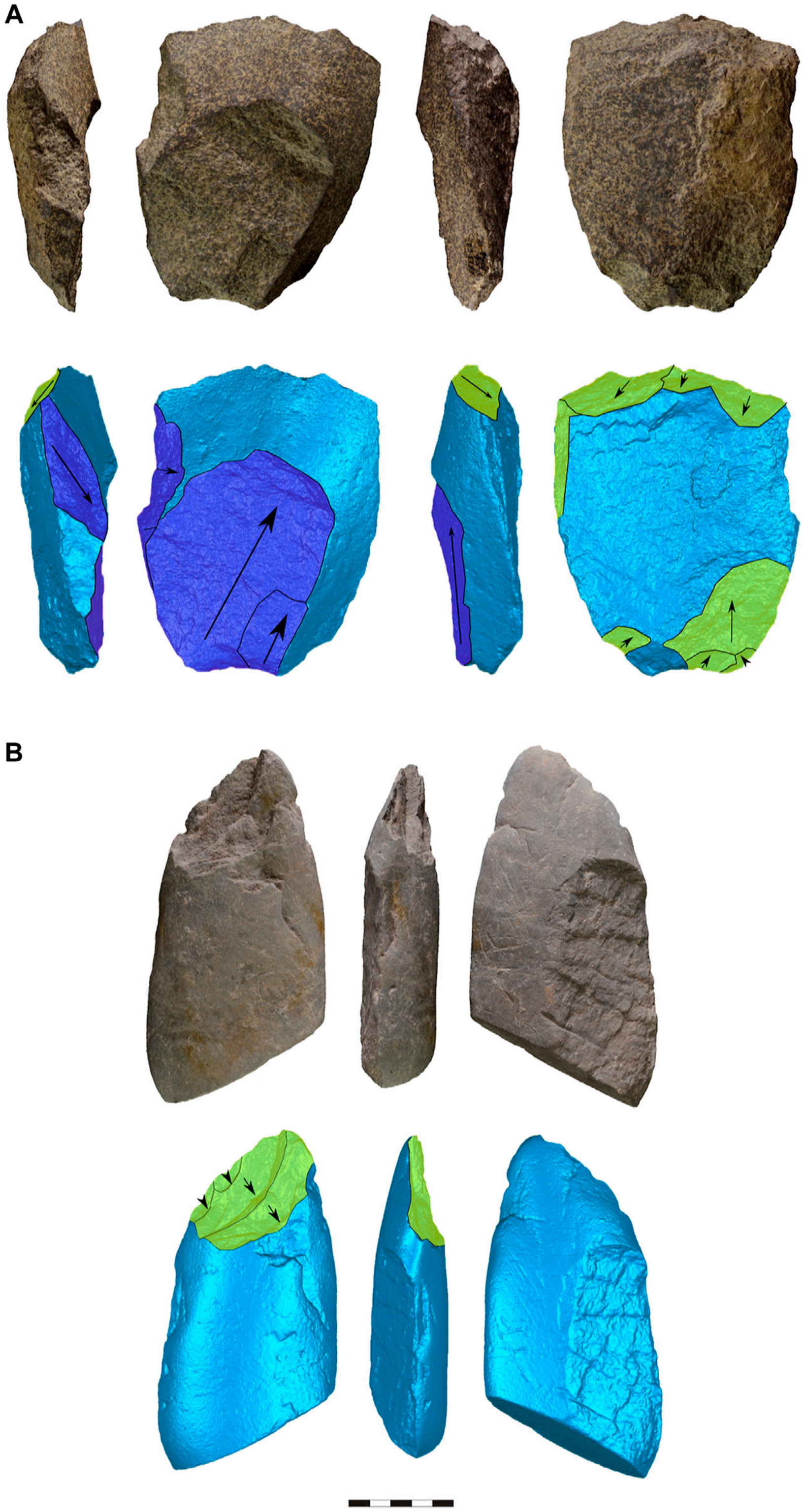

FIGURE 3
Pit 1. **(A)** Schist cleaver (ref. C1-2013-Surf-1) and **(B)** schist distal chopper (ref. C1-2019-S1-II-2-Q11-5); scale bar 5 cm.

medium-sized cobble (Supplementary Figure S3). Both show non-invasive, step-terminated removals quite constrained by the raw material schistosity plains. Among the picks, three were made on cobble (Figures 4B, 5B, 6A), one on a flake or split cobble (Figure 4A), and one was made on a chert slab (Figure 6B), and in the last case, it was not possible to determine the blank given the

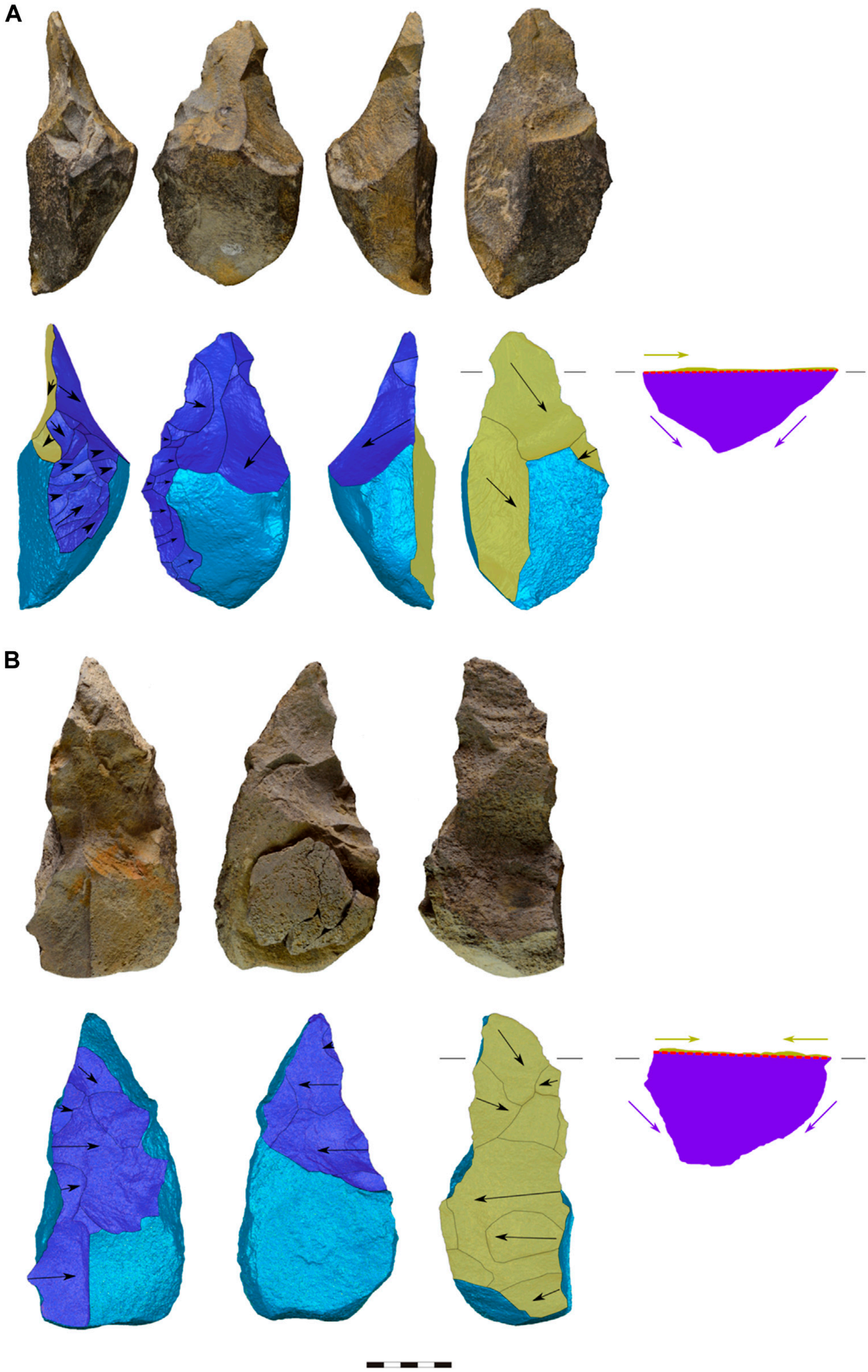

FIGURE 4
Pit 1. **(A)** Schist pick (ref. C1-2007-S1-II-2-M13-7) and **(B)** schist pick (ref. C1-2018-S1-II-2-R14-9); scale bar 5 cm.

intense shaping (Figure 5A). All the picks at Pit 1 show a triangular section and a similar shaping pattern consisting of a few invasive removals, mainly alternate and concentrated in the distal third of the tool, which produce mainly sinuous lateral edges that converge to a robust and pointed tip. Alternating flaking is also present, and even true bifacial shaping occasionally occurs for some portions of the

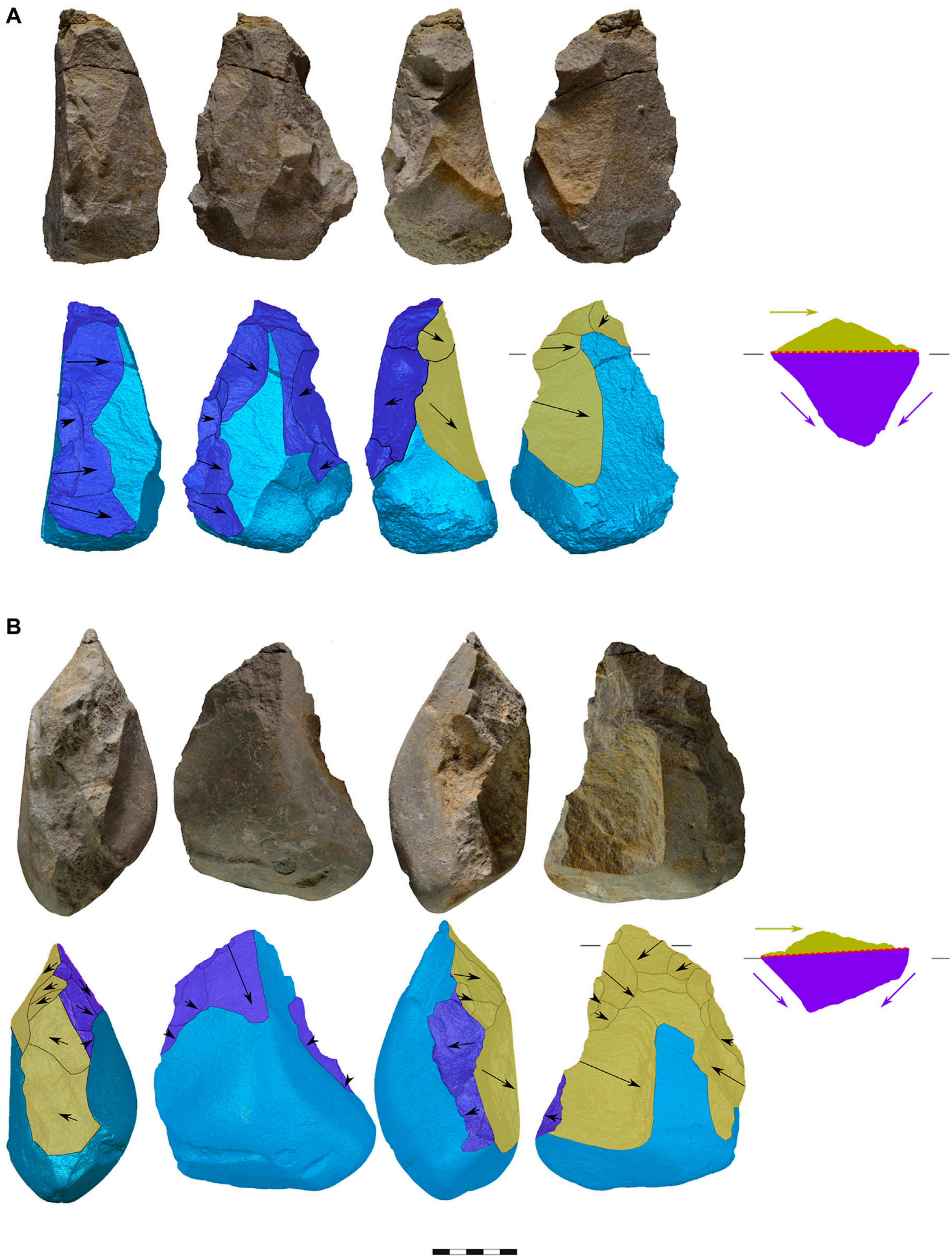

FIGURE 5
Pit1. **(A)** schist pick (ref. C1-2019-S1-II-2-P11-1), **(B)** schist pick (ref. C1-2019-S1-II-2-S10-2); scale bar 5 cm.

edges. Only one of the pieces shows a higher degree of shaping and finishing, with sagittal straight edges and a bilateral symmetry, for which it could be considered a pick-like handaxe (Figure 4A). The only cleaver is on a cortical schist flake, with a convex transversal bit slightly shaped by means of inverse removals [so we can precautionary use the "cleaver-like" term to differentiate it from

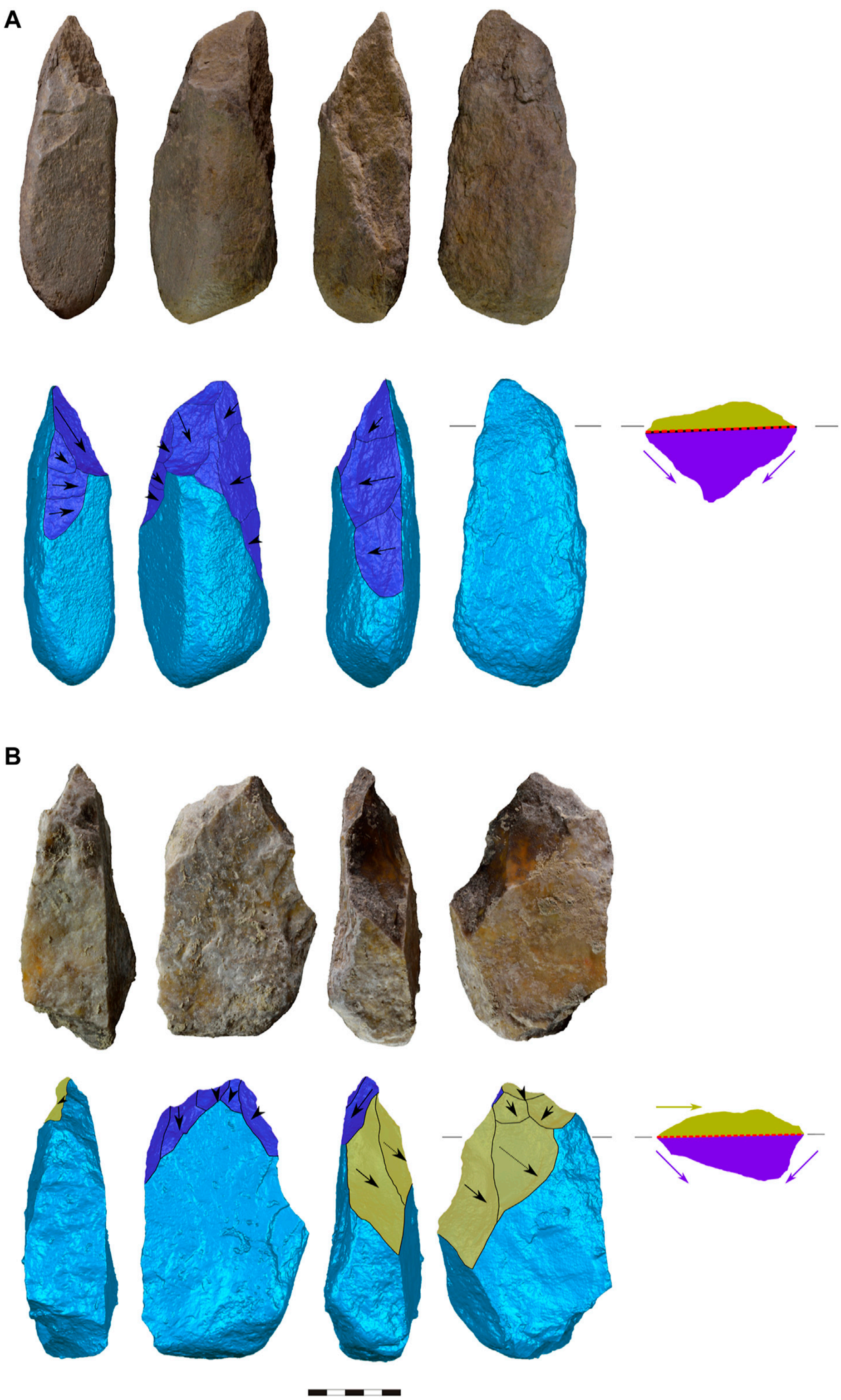

FIGURE 6
Pit1. **(A)** Schist pick (ref. C1-2019-S1-II-2-R10-5) and **(B)** chert pick (ref. C1-2020-S1-II-2-M06-2); scale bar 5 cm.

the "true" ones without a retouch on the bit (Tixier, 1957; Sharon, 2007, and references therein) (Figure 3A)]. The two remaining large shaped tools are a knife made on a quite eroded sandy schist cobble, with a convex edge, sinuous in profile, and a tool for which its heavy alteration hinders it from being properly classified. Finally, the single large flake is a side-struck one, with two previous dorsal removals.

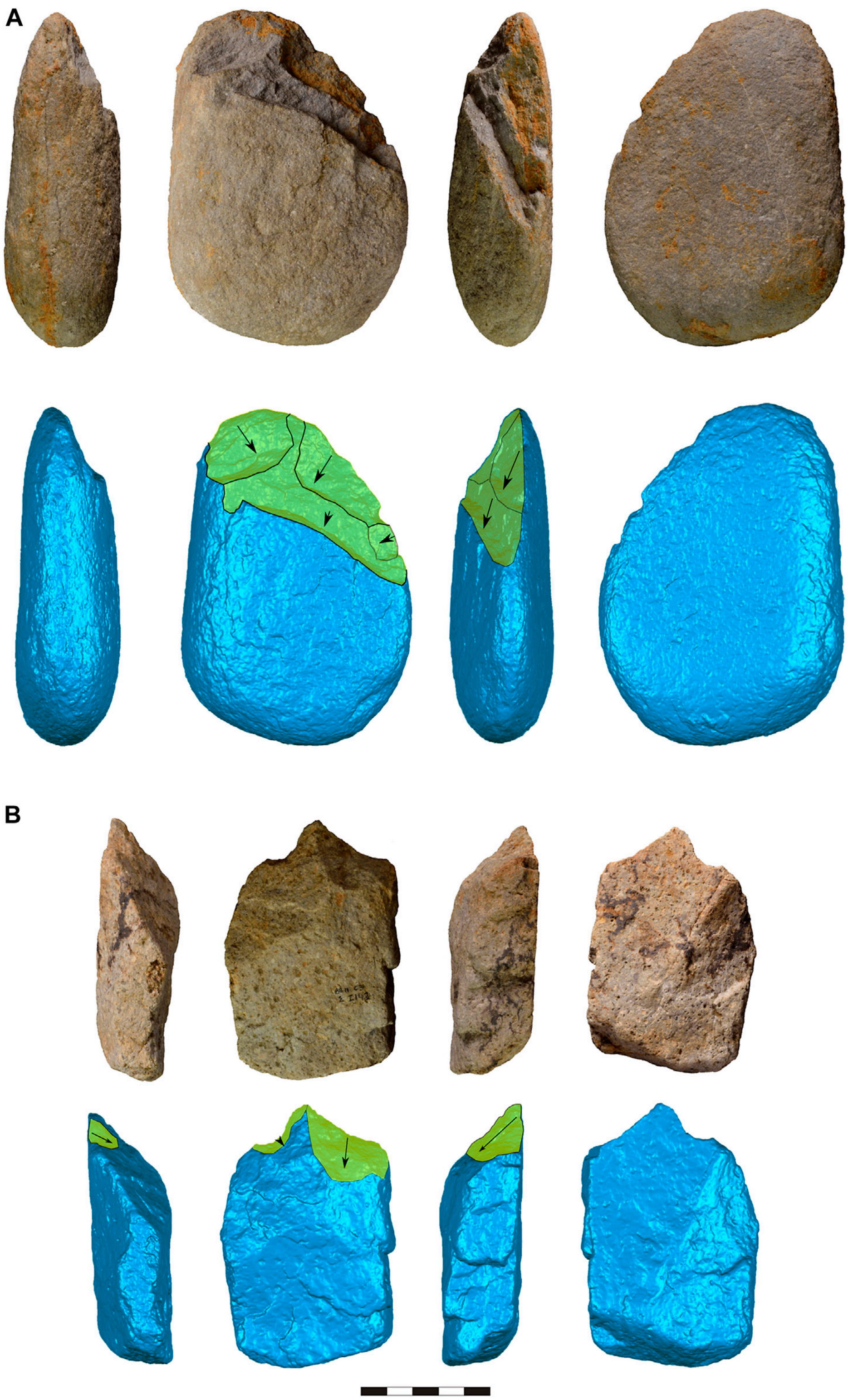

FIGURE 7
El Forn. **(A)** Schist lateral-distal chopper (ref. EF-2013-II-3-C11-1) and **(B)** granite pointed chopper (ref. EF-2011-II-2-I14-2); scale bar 5 cm.

Some opposed scars on its ventral face could be caused by the bipolar technique, and it shows a possible shaping trial on its right proximal end (Supplementary Figure S4).

The assemblage from the El Forn locality consists of seven large shaped tools, mostly on cobble. There are three choppers, one bifacial chopper, two indeterminate artifacts, and one cleaver.

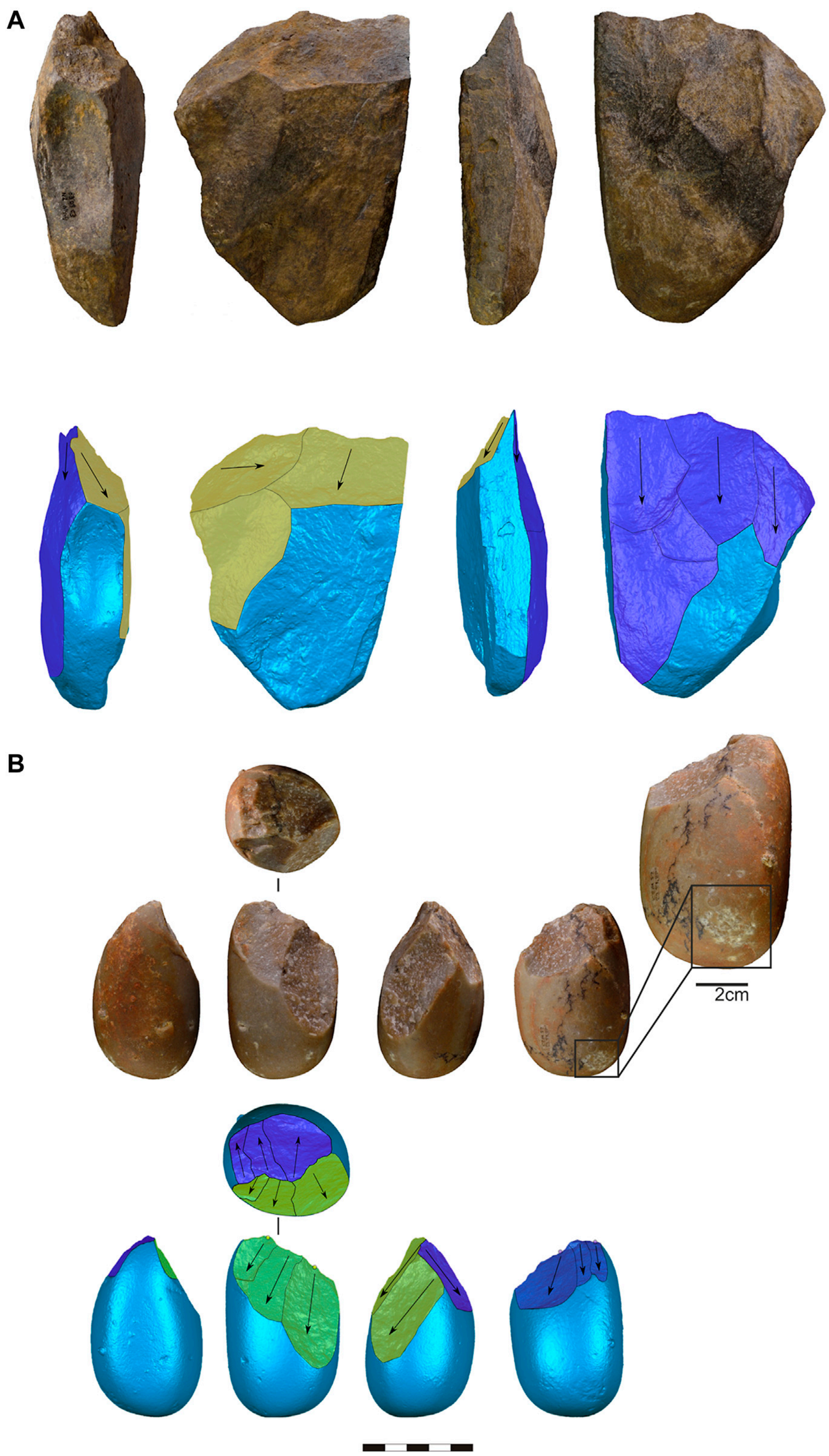

FIGURE 8
El Forn. **(A)** Schist cleaver (ref. EF-2009-II-2-N14-4) and **(B)** quartzite bifacial chopper (ref. EF-2013-II-2-H13-3); scale bar 5 cm.

The choppers show a certain typological and metric variability, with a large side-shaped form with a convex edge opposed to a thick natural back (Supplementary Figure S5), a side-distal form made on a medium-sized flat cobble (Figure 7A), and a pointed form (awl), which was made on a granite cobble (Figure 7B). The bifacial chopper was produced on a high-quality, ovate quartzite cobble,

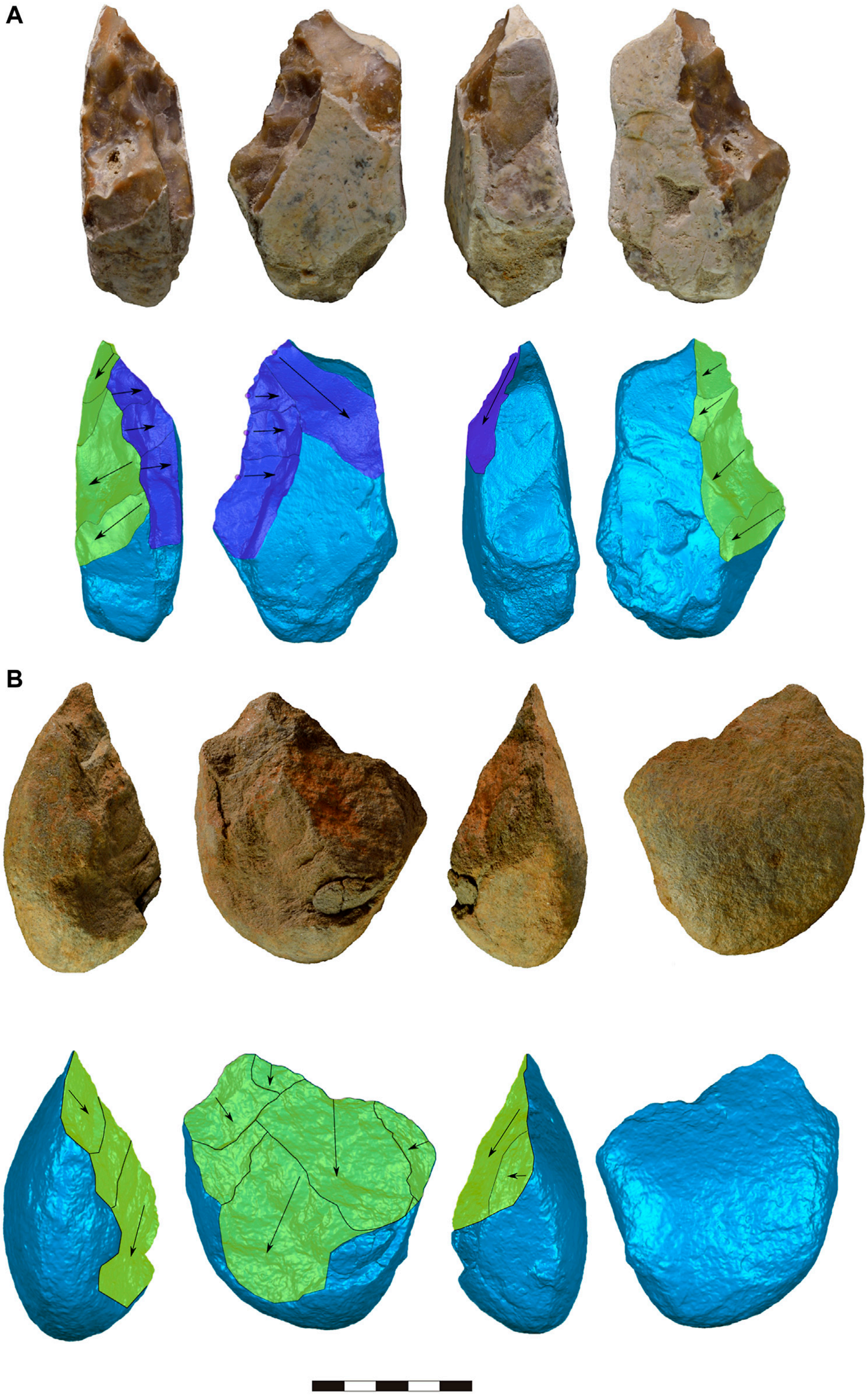

FIGURE 9
La Mina. **(A)** Chert bifacial chopper (ref. LM-2021-S2-II-2-F14-1) and **(B)** schist distal chopper (ref. LM-2013-S1-II-2-W13-1); scale bar 5 cm.

which was shaped through bifacially alternating removals. This artifact shows percussion marks on its proximal end, likely deriving from its use as a hammer in lithic knapping activities (Figure 8B). The two pieces considered typologically indeterminate are flat cobbles with some shaping, bifacial in one case, for which a bad preservation of the material prevents a correct assessment of

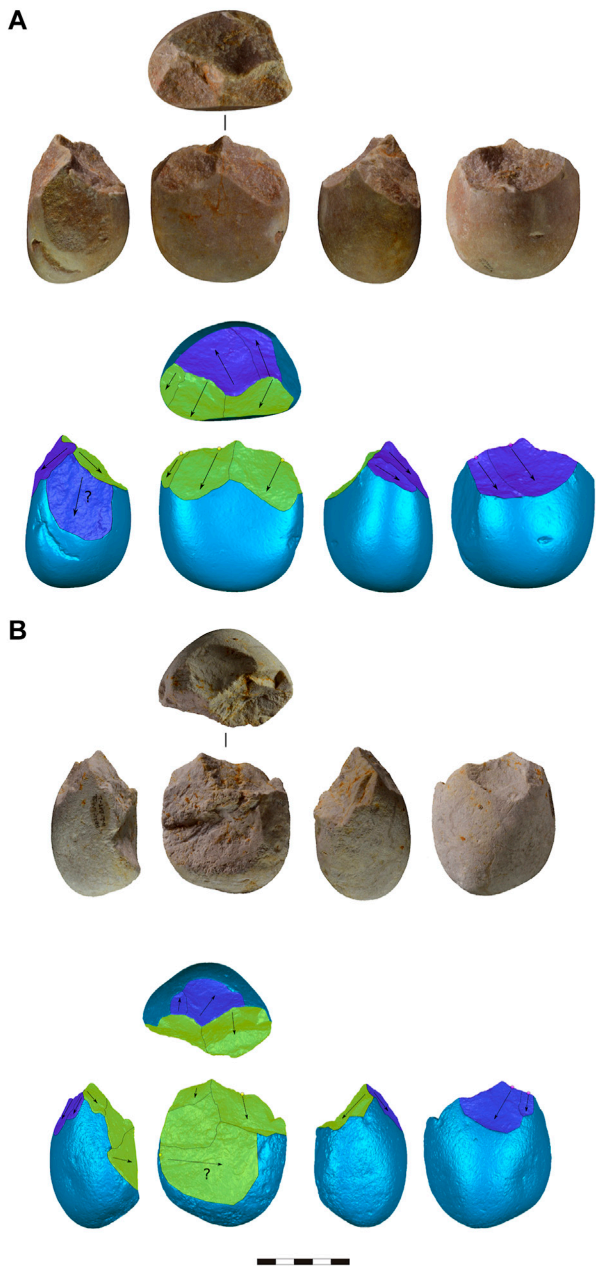

FIGURE 10
La Mina. **(A)** Quartzite bifacial chopper (ref. LM-2013-S1-II-2-U13-1) and **(B)** limestone bifacial chopper (ref. LM-2021-S2-II-2-B18-1); scale bar 5 cm.

their anthropic origin. The only Acheulean form is a cleaver (or cleaver-like tool) made on a large schist flake, probably a split cobble, with the transversal edge finely shaped through bifacial, low-angled invasive removals (Figure 8A).

Finally, the collection from La Mina consists of nine large shaped tools and one large flake. Here the raw material diversity is higher, as, apart from different varieties of schist, chert, and quartzite, dioritic porphyry and limestone were used. There are three schist choppers, pointed, latero-distal, and distal. Although the former two were made on a sandy schist and are partially weathered, they show an intensive and well-organized shaping (Figure 9B and Supplementary Figure S6); the third one shows only two distal invasive removals that create a convex edge with incurvated profile (Supplementary Figure S7). The bifacial chopper group is the best represented at La Mina, with four pieces each made of a different raw material. The one on dioritic porphyry shows an intensive shaping on its side and distal portions by means of a series of alternating removals, which led to a convex edge, very sinuous in profile (Figure11B). The edge irregularity, together with the existence of a possible knapping mishap in the form of a steep fracture opposed to the shaped lateral and the volumetric potential of the cobble, leaves open the idea of viewing the tool as an LCT in the early stages

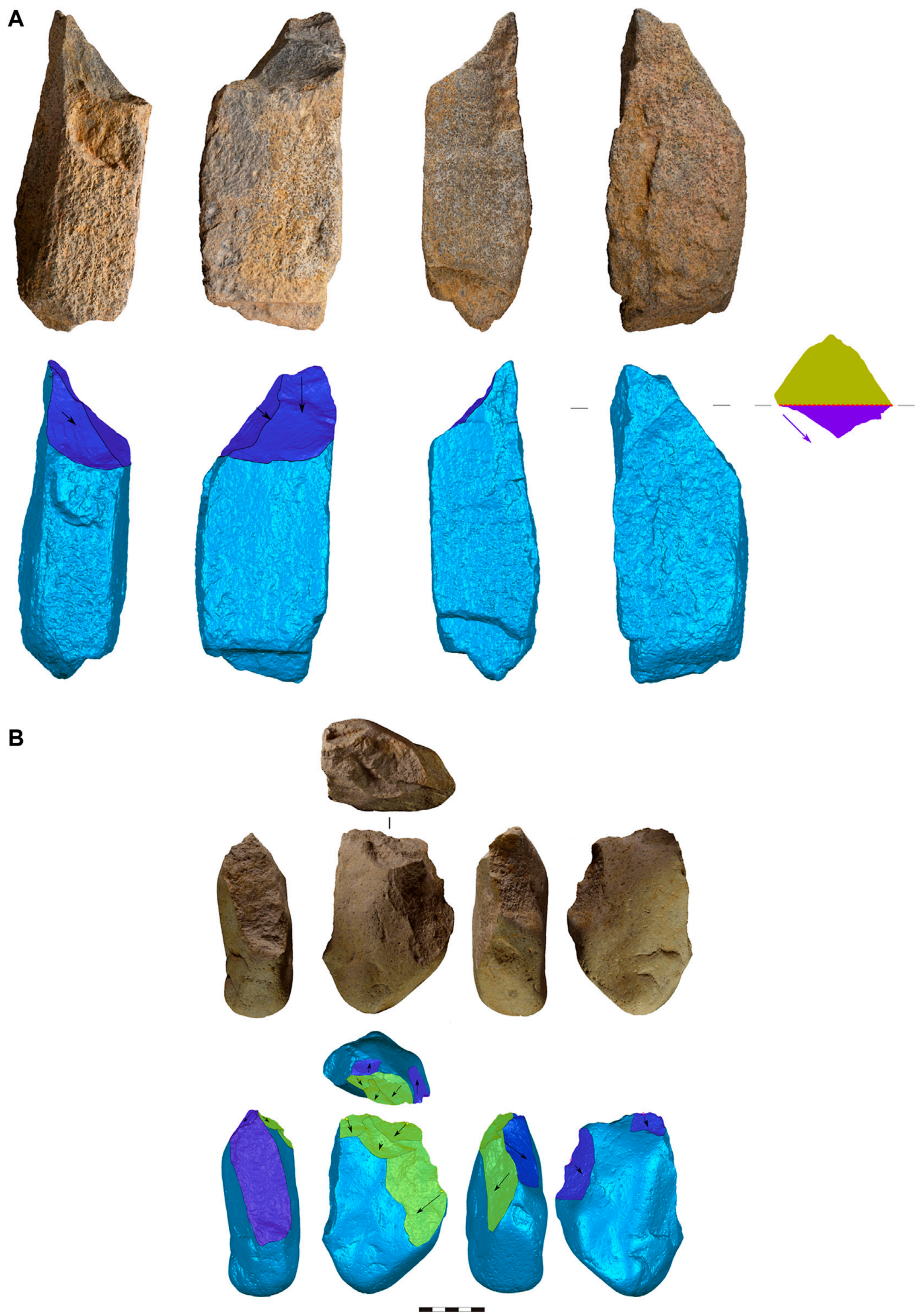

FIGURE 11
La Mina. **(A)** Schist pick (ref. LM-2022-S2-II-2-A13-1) and **(B)** porphyry bifacial chopper (ref. LM-2010-S1-II-1-O15-1); scale bar 5 cm.

of shaping. The quartzite one, like the one at El Forn, was shaped through a series of alternating, unipolar, and invasive removals, which led to a sinuous mid-angled edge (Figure 10A). The bifacial chopper made of limestone shows a similar distal shaping strategy and output, alternating removals, and a sinuous edge, in addition to a large removal on the lateral likely deriving from an earlier

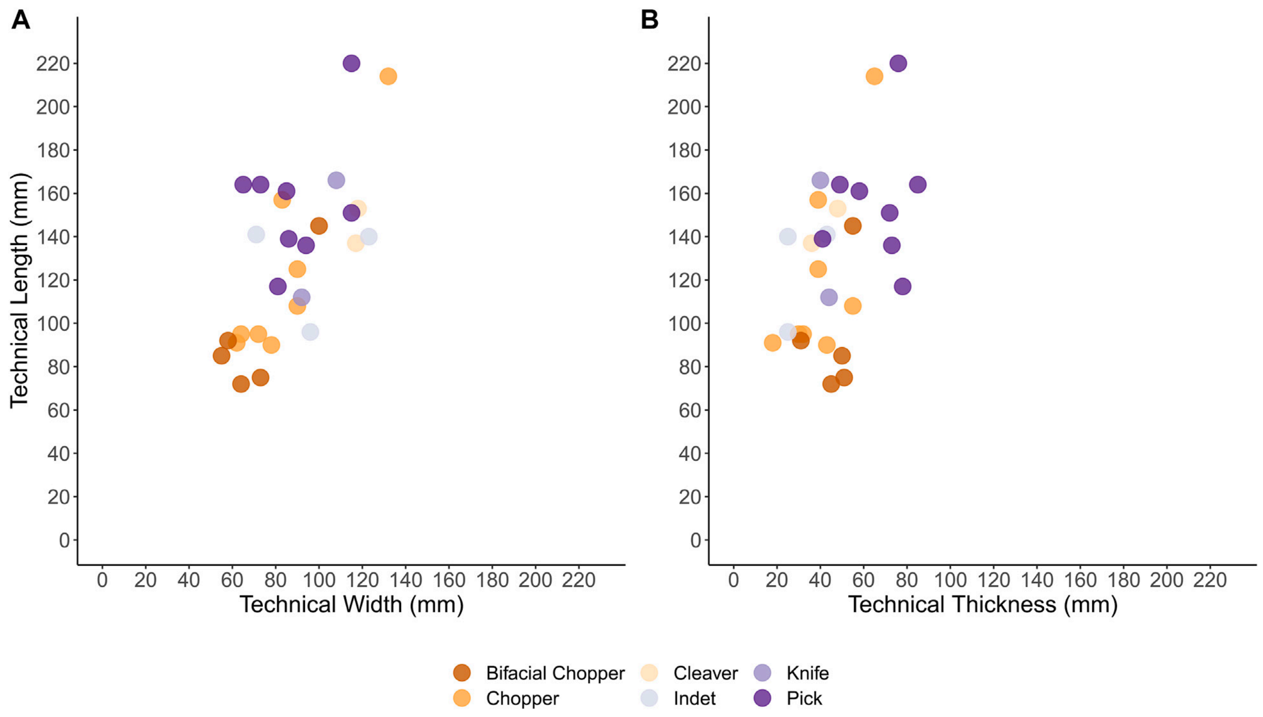

FIGURE 12
Scatter plot comparing **(A)** length and width by category and **(B)** length and thickness by category.

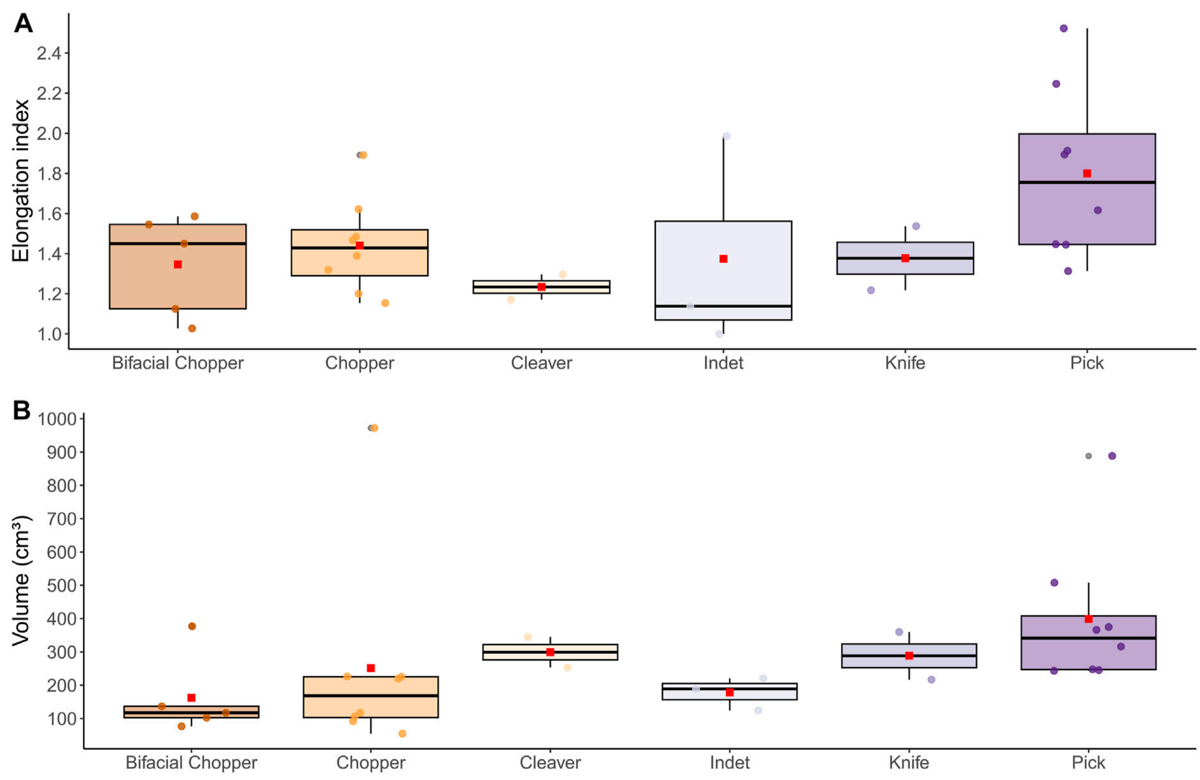

FIGURE 13
Boxplot comparing **(A)** elongation index (Length/Width) and **(B)** volume (cm^3) according to type. The red squares show the mean value for each type.

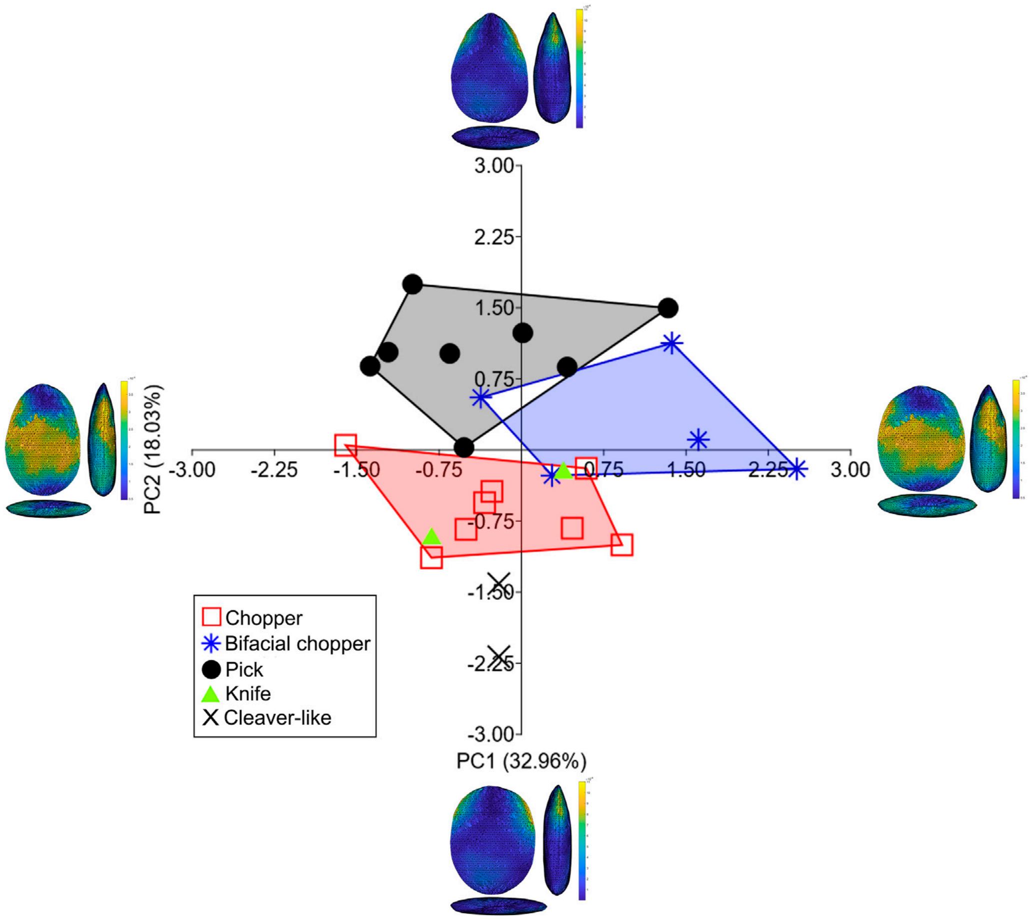

FIGURE 14
Principal component scatter plots of large shaped tools from Barranc de la Boella by type. Color coding represents the most variable landmarks in shape trends described in terms of positive and negative scores of PC1 and PC2.

TABLE 3 Intra-group shape variability analysis (measured as the mean multidimensional Euclidean distance of all artifacts from their centroid) and distribution of relative shape variability across dimensions (we excluded the indeterminate tools, refs. C1-2021-S1-II-2-L12-7, EF-2012-II-4-H12-1, and EF-2012-II-4-K13-4).

	(N)	Mean Variability	% of variability caused by x (Width)	% of variability caused by y (Length)	% of variability caused by z (Thickness)
Chopper	8	9.57	57.04	5.23	37.74
Bifacial chopper	5	10.67	31.42	11.84	56.74
Pick	8	10.73	32.77	4.18	63.06
Cleaver	2	5.64	44.98	6.18	48.84
Knife	2	8.91	65.91	3.24	30.84

percussion activity (Figure 10B). The last bifacial chopper was produced on a small tabular chert nodule, on which a series of lateral, bifacially alternating removals created a concave and sagittally straight-to-sinuous edge (Figure 9A). The picks are represented by two pieces. One was made on a large and thick, rounded coarse-grained schist slab, where two invasive removals and some additional lateral shaping define a marked distal trihedron (Figure 11A), while the second is crude, made of chert, with poor shaping that produced a not-prominent tip (Supplementary Figure S8). The remaining large shaped tool is a knife made on a sandy schist overshoot flake; there, although the erosion prevents an accurate reading, a sequence of bifacial removals created a convex and sinuous side working edge (Supplementary Figure S9).

The single flake larger than 100 mm, on schist, shows a previous dorsal removal orthogonally arranged with respect to its technical axis and provides an example of large schist flake production (Supplementary Figure S10).

It is important to note that several of the pieces show macroscopic damage on the edges or surfaces likely produced by their use. The surfaces of the schist and limestone artifacts have poor preservation compared to the excellent surfaces of the chert and quartzite objects. However, apart from the aforementioned percussion marks on two of the bifacial choppers, possible macroscopic use-wear was observed on nine large shaped tools (on two picks and one unifacial chopper from Pit 1; one unifacial chopper and one bifacial chopper from El Forn; and one unifacial chopper, one bifacial chopper, and two picks from La Mina). The preliminary microscopic analysis showed very promising results at least on three tools: the chert pick from Pit 1, with a very pronounced edge rounding only on the tip of the tool (Supplementary Figure S11); the quartzite bifacial chopper from El Forn, with intensive crushing in all the exposed portions of the distal edge (Supplementary Figure S12); and the small chert bifacial chopper from La Mina, where a small portion with intensive and continuous scarring has been documented on a generally fresh edge (Supplementary Figure S13).

4.2 Metrical distribution, volume, and blank selection

From a metrical point of view, there are several notable characteristics in the studied assemblage. There are clear differences in the dimensional measurements according to tool typology. Thus, bifacial choppers are the group with the smallest dimensions (Figure 12, Supplementary Tables S6–S8), both in terms of technical length and width, as well as in terms of volume (Supplementary Table S10). Also, they have a greater thickness compared to most of those tools, apart from the picks (Supplementary Table S9).

On the opposite side, we find the picks and cleavers, with generally larger technical dimensions, with central values (mean and medians) approximately 150 mm in length and 90 and 117 mm in width, respectively (Supplementary Tables S6, S7). The picks present a generally larger remaining volume than the rest of the tools (Figure 13, Supplementary Table S10). These differences are statistically significant in the central values (K-W = 11.18, df = 5, $p = 0.047$), although the p-value is very close to 0.05. However, these differences are also noticeable after calculating the elongation index (EI = technical length/technical width, Supplementary Table S9). Therefore, a very marked allometric pattern can be observed between the picks and the rest of the tools, with the picks being relatively longer than wide (Figure 12A). Meanwhile, the two large flakes present larger dimensions in technical width than in length, which explains the very low EI values, although they present similarities with the picks in terms of size or volume.

Considering the large amount of preserved cortical surface and the generally restricted shaping in specific sectors of the large shaped tools, these morphometric differences provide valuable information about the blank selection strategies of the hominins from Barranc de la Boella. To produce bifacial choppers (chopping tools), blanks with an oval-ellipsoidal morphology were selected. In some cases, these artifacts bore impacts and battered marks, indicating their previous or subsequent use as hammerstones. In addition, a remarkable feature of these chopping tools is that several raw materials are used, generally marginal within the assemblage, such as limestone, quartzite, and porphyry. This is unlike most of the large shaped tools made in different varieties of schist. Considering the toughness, morphology, and size of these materials, managing these blanks volumetrically through knapping is not easy. In this sense, the development of alternate and/or alternating methods demonstrates a great capability on the part of these hominins to overcome the restrictions of the raw material.

The unifacial choppers exhibit great variability in both dimensions and volume, as well as in the EI. No apparent pattern is discernible in terms of morphology and size of the blank.

Conversely, especially in some picks, natural shapes with a trihedral tendency are selected, which require minimal further modification (sometimes only a series of unifacial extractions) to achieve the desired morphology. This selection reduces the intensity of the shaping, restricted to the tip, which can in some cases give rise to similarities from a technological point of view with other typologies such as choppers (Figures 3B, 6A). In other cases, the shaping of the picks is carried out through longer and more complex series, while in still other cases, large flakes are obtained for subsequent shaping. The importance of the selection process within the technical system of these hominins is also evident in the large flakes, both modified (cleavers and knives) and unmodified. Thus, there is a morpho-dimensional homogeneity in the flakes used as cleavers and knives. This homogeneity is visible in all the metric aspects considered here (dimensions and volume), with a major difference in width because cleavers are slightly wider than knives, which translates into a lower EI.

However, when comparing the blanks of these tools with the large flakes without retouching, we observe how the latter are 1) thicker, 2) technically shorter (according to the technical axis of the flake), and 3) larger in volume (Table 2). This suggests a certain criterion when selecting large flakes for further shaping, especially considering that these instruments are already modified when transported to the sites.

4.3 Morphometrical analysis

To assess the intra-group variability in the shape of the large shaped tools, we applied the geometric morphometric techniques to 24 LCT 3D models, excluding fragmented and indeterminate tools that had lost their final shape. The PCA pointed out the high heterogeneity of this assemblage and clear morphometrical distribution of tool types. More than 87% of the variability was explained by the first 10 principal components (Supplementary Table S11). The best morphological characterization of this assemblage resulted from the combination of PC1 (32.96%) and PC2 (18.03%) (Figure 14). PC1 represented the transition from wider and thick shapes on positive values to elongated and thinner tools on negative ones. PC2 gathered variation from pointed distal ends in thicker shapes in positive values to wider convex parts in thinner tools.

According to this analysis, there is a clear distance between the distributions of the three main generic tool types: choppers, bifacial choppers, and picks. The interpoint distances between the mean shapes of these groups are statistically significant (rank sum = 112; $n1 = 8$; $n2 = 5$; $p = <0.01$/rank sum = 168; $n1 = 8$; n2 = 8; $p = <0.01$). Choppers are located on the lower part of the graph. Their morphologies are distributed along PC1, with a clear variation in tool width (Table 3). Nevertheless, they are mainly thin cobbles, and shaping creates widely convex distal parts. In contrast, picks are distributed on the upper part of the graph. They present the highest intra-group variability, with thinner and pointed shapes, and their maximum variability is focused on thickness. Bifacial choppers are distributed on the right side of the graph, presenting their major variation concentrated on tool thickness. They are the thickest tool type, and, as the second major intra-site variability group, their distal morphologies range from convex to more pointed distal ends. Knives are integrated within the scatter group of choppers/bifacial choppers. The two cleavers appear clearly apart from choppers and picks, being the widest and thinnest tools.

A different aspect related to tool morphology is their degree of symmetry (Supplementary Table S12). As we stated in the methodological section, we focus on the deviation from bilateral and bifacial symmetry, the planform and section irregularities. In general terms, choppers, bifacial choppers, and picks present a high coefficient of variation (CV), which indicates a high intra-group variability, which in turn means a low degree of symmetrical standardization. Nevertheless, picks are the least symmetrical tools. They present 52% less bifacial symmetry than choppers, showing clear differences between the upper-middle and lower-middle parts of tools. Section irregularity is higher in picks. Both edges present planform differences in all cases, but knives present the greatest degree of difference, with 56% more irregularity in one of their edges. However, due to the low number of cleavers and knives, we cannot evaluate their statistics.

5 Discussion

The results presented in this study reflect the systematic research program carried out since 2007 in the late Early Pleistocene deposits from the Barranc de la Boella site. Because of the significance of the large shaped tools for the cultural ascription of the site in the frame of the earliest presence of the Acheulean techno-complex in Europe, we have focused on the collection of these elements recovered so far at Unit II (0.99–0.78 Ma). After summarizing the characteristics of these large shaped tools, we will discuss the features that make Barranc de la Boella unique in the known late Early Pleistocene archaeological record from Europe and distinguish it from the rest of known ancient Acheulean sites in this continent, which are all dated at the Middle Pleistocene. The discussion will support the idea of an Early European Acheulean and will lead us to consider aspects of its possible origin in terms of technological transitions, hominin dispersals, and technological convergence phenomena.

Although the two main localities at Barranc de la Boella, Pit 1 and La Mina, are still under excavation in layers containing these assemblages, at this time, we have enough solid data to adequately depict a fluvial-deltaic landscape, to report on its paleoenvironmental features, and to identify the impact that early hominins had on it. Research conducted so far enabled us to document hot spots of activity in that landscape, which vary in spatial and temporal resolution. They include high archaeological (so behavioral) resolution records like Pit 1, together with illustrations of cumulative palimpsests indicating scarce but considerable human activity as an accumulator or a modifying agent (the El Forn and La Mina localities).

At Pit 1, preliminary spatial observations enabled us to distinguish a close relationship between the faunal remains and the scatter of lithics (Figure 2). The percussive material and the large shaped tools seem to be mainly concentrated around the mammoth remains, while the chert cores and flakes exhibit two different concentrations. The denser one surrounded the mammoth remains, and the other one, found towards the north of the excavated surface, was accompanied by more dispersed faunal remains from different taxa. Future spatial studies are needed, among which lithic refitting stands out, to explore the possible temporal connection with these two lithic clusters.

The lithic assemblage from Barranc de la Boella Unit II includes, so far, 966 elements and shows general similarities among the three explored localities. In all cases, the predominant raw material is chert (86.7%), while a group of secondary materials includes schist (6.5%), quartz (3%), quartzite and sandstone (1.1%), and a third group, which represents less than 1% of the total assemblage, includes granite, lydite, porphyry, and limestone. All these raw material types are now accessible in the adjacent alluvial environment, although a comprehensive petrographic study is required to delve further into the internal variability and particular supply strategies.

The distribution of the lithic collection of Barranc de la Boella by technological groups and raw materials (Table 1) shows a good representation of the percussive material (4.7%), the predominance of the core-and-flake group (<90% if we consider the cores, most of the small and medium-sized products, and the knapping angular fragments), and the low weight of the large shaped tools (2.9%). Moreover, we identified a differential selection and management of raw materials in which there is a prevailing use of chert for flake production (91.2% of the cores and a similar weight for the different classes of detached pieces), in contrast to a clear correlation of the rest of the raw materials with percussive elements and large shaped tools.

The previous analysis of the core-and-flake group (Mosquera et al., 2016), as well as the general metric data provided in this study (Supplementary Tables S2–S4), and recent research on the core reduction (Lombao, 2021) revealed exploitation strategies focused on the production of small and medium-sized products neither morphologically nor typometrically standardized. While there is a certain degree of variability in knapping strategies (mainly unifacial unidirectional and bifacial orthogonal), there are some examples of bifacial centripetal cores that show more efficient and organized volumetric management. These imply knapping sequences not strongly constrained by the size or shape of original raw material blanks. A significant proportion of those products were subsequently modified by retouching (6.8% of the whole sample), mainly in the form of denticulates and, to a lesser extent, scrapers. It is worth noting that at Pit 1, the development of the *in situ* chert knapping activities has been attested, thanks to the abundant knapping debris, the spatial distribution of the materials, and the identified refits (Mosquera et al., 2015).

As stated in the introduction, in this study, we used the category of large shaped tools, a term used by Kleindienst (1962) and Isaac (1977), to refer to a "primary class" with all the shaped elements of large size, which, according to these authors, would include "secondary classes" referring to the large cutting tools (LCTs) and the heavy-duty tools. As presented in the results section, the predominant types in the Barranc de la Boella assemblage are choppers and picks, both classed by these authors as heavy-duty tools, while the types they consider as LCTs are scarcer.

Unifacial choppers are present in all Barranc de la Boella localities, mainly made of different varieties of schist and, in one case, of granite. They are made on flat cobbles variable in size and show primarily distal or latero-distal shaping, with only two cases of pointed morphology. The absence of recurrence in their flaking, the absence of products resulting from their knapping, the flatness of most of the blanks, and the preliminary functional data derived from macroscopic observation and primary microscopic screening are proxies that make us assume that these elements are real tools and not cores or the by-product of flake production. In fact, their shaped edges are mainly low angled, with a mean of approximately 55° (P1: 42°, EF: 53°, and LM: 68°).

The bifacial choppers are present only at El Forn and La Mina localities. This is the group with higher variability in terms of raw materials, as they are present in quartzite (two elements), porphyry, limestone, and chert (one element each), but they are absent in schist. As observed in Section 4.2, apart from the porphyry case, these elements were produced on small, globular cobbles—quartzite and limestone—and were shaped through bifacial alternating removals, resulting in mainly lateral and distal convex edges, sinuous in profile. These edges present significantly higher angles than unifacial choppers, with a mean of 70°. Again, the fact that there are no flakes originating from these blanks, together with the preliminary functional observations, allows us to think of them as tools rather than cores. In addition, at least in two cases (the quartzite one from El Forn and the limestone one from La Mina), they were also involved in percussive activities.

Following the choppers, the picks are the best represented and more characteristic large shaped tools at Barranc de la Boella. This tool type has unequally been classed in the literature. While some authors included them in the heavy-duty secondary class (Kleindienst, 1962; Isaac, 1977), they are commonly counted among the LCTs in more recent works (e.g., Sharon, 2007; Kuman, 2019; Herzlinger et al., 2021, to mention but a few). However, there is general agreement on considering them bifacial forms (Leakey, 1971), characteristic of the Acheulean (Isaac et al., 1997; Stout, 2011; de la Torre, 2016, and references therein).

Picks at Barranc de la Boella are mainly made on medium to large-sized schist cobbles, although at Pit 1, there is one made on a large flake probably obtained after a cobble of this material split and another one for which the blank remained undetermined. The two picks of chert are on a slab (Pit 1) and on a possibly fragmented cobble (La Mina). Overall, these pieces represent the biggest and most elongated tools at Barranc de la Boella (Figures 12, 13). They present a certain morpho-technical standardization. On the one hand, they seem to follow a pattern in terms of blank format selection, likely to reduce the necessary further modification. They also share a triangular cross-section and a similar shaping pattern consisting of a few invasive removals concentrated in the distal third of the tool. This shaping is predominantly alternate, although alternating bifacial flaking has been attested. Outcomes show robust thick sections, quite sinuous lateral edges, and scarce bifacial and bilateral symmetry. The one of schist from La Mina, made on a large, rounded slab, stands out for its dimensions and weight as well as for its simplicity, as the shaping was basically limited to two large invasive distal removals and some minor arrangement on the lateral.

The collection also features two schist cleavers that do not correspond with Tixier's classical definition that implies an untrimmed bit (Tixier, 1957). Both blanks indicate skillfulness in large flake production in the form of splitting cobbles (El Forn) or giant core reduction (La Mina). Although present in both cases, the shaping is especially significant for the former, on which the transverse bit shows bifacial invasive flaking.

The two pieces classified as knives (Pit 1 and La Mina) were made of schist, and currently show postdepositional alteration in the form of loss of grain cohesion. Both are on large cortical flakes, with characteristic asymmetry and one steep and blunt side opposed to the shaped edge. Only in one case (La Mina) is this shaping clearly bifacial.

Apart from the cleavers ($n = 2$), the knives ($n = 2$), and one pick, the skill on large schist flake production is attested by two unretouched elements (Pit 1 and La Mina). Both the cobble splitting and the management of giant cores resting on the ground appear to have been applied, perhaps involving some throwing technique (Li et al., 2017). However, such giant cores are absent in the record, and the sample of products is too small ($n = 7$) to raise conclusive observations. We must highlight that classical handaxes, in the sense of symmetrical tools with two lateral convex edges converging in a more or less marked tip, a lenticular cross-section, and shaped all along their perimeter through invasive bifacial removals that cover its whole surface, are, to date, absent in the collection of Barranc de la Boella.

Despite the described crudeness of the shaped tools at Barranc de la Boella, deriving from a limited shaping, a reduced symmetry, and a low degree of finishing, a certain standardization can be observed. This issue is visible in terms of raw materials management, morpho-technical procedures and outputs represented. As commented on in Section 4.2, such standardization can be particularly seen in the selection of suitable raw material formats for the production of some types. Here, the case of the picks stands out. While their shaping is limited to the creation of a pointed tool, the capacity to obtain relatively homogeneous forms through different technical processes is evident. These include quite intensive shaping of a cobble, selection of the more suitable blanks that require only a slight modification, and the production of large flakes for subsequent shaping. These processes can be considered a reflection of a high cognitive flexibility (Sharon, 2009).

It is important to note that at Barranc de la Boella, there is a spatiotemporal fragmented reduction sequence for the whole set of large shaped tools. Although the raw materials were locally available, the manufacture of the large shape tools seems to be allochthonous and independent from the chert flake production that took place at the site. This implies a differential transport of materials, hominin mobility, and, in the end, forecasting and technical planning. Indeed, this pattern has been observed in other European Acheulean assemblages (Bourguignon et al., 2016; Moncel et al., 2019; 2020b; 2021) and specifically reported in Iberian Middle Pleistocene sites, for instance, Galería and TD10.2 in Atapuerca (Ollé et al., 2013; García-Medrano et al., 2017), Áridos in Madrid (Ollé, 2003), or La Cansaladeta (Ollé et al., 2016), in the same Francolí basin as Barranc de la Boella.

In addition, the coexistence of the two *chaînes opératoires* identified at Barranc de la Boella has also been reported in African Early Acheulean sites such as Gadeb (de la Torre, 2011) or Thomas Quarry I (Gallotti et al., 2020), where reduction sequences devoted to small size debitage appear together with an important group of LCTs, in which symmetry and bifacial shaping are only occasionally present. In fact, such a coexistence may well reflect a functional complementarity. At Barranc de la Boella, the preliminary results from the low-power approach microwear analysis of the pieces presented in this study, which indicate traces of forceful activity likely related to the exploitation of the animal carcasses, may supplement the butchery use-wear traces identified by a previous study on a sample of small and medium-size chert flakes from Pit 1 (Mosquera et al., 2015).

Overall, the technological features described in the collection from Barranc de la Boella allow us to support the formerly proposed idea of a European Early Acheulean (Mosquera et al., 2016). This is based on the technological parallels with Early Acheulean African sites, as well as the differences with respect to what is observed in contemporaneous sites European sites, and the significant differences with the technological features recorded at the Acheulean sites dated at the beginning of the Middle Pleistocene.

As summarized elsewhere (Presnyakova et al., 2018), in Africa, the scarcity of bilaterally and bifacially symmetrical large shaped tool forms helps to distinguish Early Acheulean assemblages from later ones. Stout (2011) argued that, in contrast to the complex production process of large shaped tools younger than 1 Ma, those of the Early Acheulean indicate significantly simpler production sequences. Even though the diachronic variability of handaxe morphology is still debated (Caruana, 2020), in Africa, the presence of pick-like pieces with triangular sections and little management of the central volume is commonly presented as a distinctive trait of the Early Acheulean (de la Torre et al., 2018b; Kuman, 2019; Gallotti et al., 2020). To our knowledge, Barranc de la Boella is the only Early Pleistocene site in Europe showing this techno-typological feature.

In Western Europe, the onset of the Acheulean has traditionally been poorly known due to the limited archaeological evidence before 0.7 Ma, as well as the relatively few sites dating from the Early to Middle Pleistocene transition to 0.5 Ma. The latter research gap has considerably disappeared in recent times (Moncel et al., 2013; 2019; 2020a; 2020b; Moncel et al., 2015; Antoine et al., 2019), while the former is still a drawback. In this sense, Barranc de la Boella is, to date, one of the few sites providing data.

The closest known European parallel to Barranc de la Boella is the site of Notarchirico (Southern Italy), whose oldest layers are dated at c. 0.7 Ma (Moncel et al., 2020b). In fact, some of the main technological features described at Notarchirico can be seen on the large shaped tools from Barranc de la Boella. These include a poor bifacial management and bilateral equilibrium (asymmetry), both face-to-face and alternating shaping, often sinuous lateral edges converging on a tip with specific management, absence of evident resharpening, as well as the existence of many pebble tools, including choppers and cleaver-like forms. However, more evident management of the bifacial volume has been reported at Notarchirico than at Barranc de la Boella (Moncel et al., 2019; 2020b; Santagata et al., 2020). Other close parallels could be seen in the French sites of La Noira (c. 0.7 Ma; Moncel et al., 2020a; Moncel et al., 2021) and Moulin Quignon (c. 0.65 Ma; Antoine et al., 2019; Moncel et al., 2022), in which, importantly, handaxe production involving patterned bifacial and bilateral equilibrium is already attested.

Human dispersals and associated cultural transmission phenomena have been widely explored. Thanks to discoveries at new sites such as Barranc de la Boella, some new observations can be made to contribute to this research topic. In a previous article, we commented on several possible scenarios (Mosquera et al., 2016) that have been later summarized with the idea that Barranc de la Boella "*. . .could represent an early attempt of bifacial shaping and local onset of crudely made bifacial tools. . .*," or "*. . .could also represent the arrival of a non-local hominin group and technology*" (Moncel et al., 2020b:12).

So far, there is no evidence of any transitional feature pointing to a local evolution from an older and simpler Mode 1 technology. In the north-east of Iberia, such assemblages are scarce, and the ones with similar chronology, for example, Gran Dolina-TD6 in Atapuerca, show very different characteristics from what is documented at Barranc de la Boella (Mosquera et al., 2018; Lombao et al., 2022). In this sense, future work at the lower levels of Unit II at La Mina could provide interesting clues.

Of course, convergence phenomena can also be possible. This hypothesis would imply the innovation of similar bifacial morphologies in unrelated places and moments instead of being caused by human migrations or cultural diffusion. However, the idea of a single but variable cultural tradition lasting a very long period (Lycett and Gowlett, 2008) seems to gain support from recently published research. Shipton interprets the western Acheulean as a "*coherent cultural entity that seems to have spread from a single source region, and with regionally consistent variations suggesting it was maintained through social transmission*" (Shipton, 2020:13). Based on statistical assessment, Key (2023) perceived the Acheulean as a temporary, cohesive, single cultural tradition with no interruptions in the social transmission of information during either its earlier or later periods. Even studies that attribute coincidences in large core technology to convergent cultural evolution reject this mechanism as being responsible for the similarities in the Acheulean end products such as handaxes and cleavers (Sharon, 2019).

Therefore, the idea of a diffusion/dispersal of the Acheulean into Western Europe earlier than previously known, mirroring the situation in Asia (Pappu et al., 2011), must be considered. Although several possible dispersal routes for such an event have been discussed (O'Regan, 2008, and references therein), research recently being carried out in the Aegean zone (Sakellariou and Galanidou, 2017; Tourloukis and Harvati, 2018) makes us consider the coastal route following the northern Mediterranean basin as very plausible.

As highlighted when commenting on the role played by technology in human expansions through the "Out of Africa Technological Hypothesis" (Carbonell et al., 1999), the oldest examples of Acheulean evidence in Western Europe (at that moment, Notarchirico and Caune de l'Arago) showed evolved techno-typological features of that technology. In this sense, we later draw specific attention to the absence in Europe of a set of "archaic traits" present in sites such as 'Ubeidiya (crude handaxes, pick-forms, and spheroids, along with choppers) (Carbonell et al., 2010:39). Therefore, we supported the idea of a first expansion of Mode 2 in the Near East (represented by 'Ubeidiya at 1.4 Ma), which would not have been strong enough to reach other Eurasian regions. A more successful second expansion would have occurred later, around 0.8 Ma, represented in the Levant by the large flake Acheulean assemblage of Gesher Benot Ya'aqov (Goren-Inbar et al., 1992; Goren-Inbar et al., 2000), and with echoes in eastern Asia in sites as Bose (Hou et al., 2000), and, in its turn, being the origin of the Western Europe Acheulean.

The new evidence presented in this study allows us to make some inferences to build on the cultural relationships between the Levantine and Western European records. The chronology and the described technological features enable us to hypothesize the record of Barranc de la Boella as the reflection of an "out of Africa event" with an Early Acheulean technology unprecedentedly recorded in Europe. This implies adding an important nuance to the hypothesis on the onset of the European Acheulean proposed by Moncel et al. (2020a) by clearly pointing to the technology represented by 'Ubeidiya as the key referent for what we have recorded c. 1 Ma ago in the eastern coast of Iberia. 'Ubeidiya, in fact, holds the most comprehensive known record of Early Acheulean culture outside Africa (Herzlinger et al., 2021) and shows a set of features that we also described for the Barranc de la Boella assemblage. Similarities can be seen in terms of the management of raw materials that overcomes their constraints, a definite preference for producing specific tools on particular rock types, a technological forecast and certain planning capacities visible from the large-tool technology, and a spatiotemporal fragmented reduction sequence for these elements, with initial production phases located beyond the sites. This goes together with a clear low modification intensity of the flake blanks, a less standardized core reduction than in younger Acheulean occurrences, the presence of two general classes (the handaxe and the non-handaxe groups, the latter including the well-represented picks), and a preferential investment in the design of the final tool given to its tip (Herzlinger et al., 2021). As previously mentioned, Barranc de la Boella is the only Early Pleistocene site in Western Europe to exhibit this particular collection of technological features. To explain how this came about, we suggest that gradual diffusion may have occurred along the north Mediterranean coastal basin from the Levant to Southwestern Europe, where the new technology may have coexisted with a well-established Mode 1.

Finally, the time gap between the onset and dispersal of the Acheulean in Africa and its first appearance in Western Europe is not easy to explain with the current data. Geographical barriers and other paleoenvironmental constraints may be argued, as may climatic variations (glaciations effect, changes in the sea level, etc.), the fact of being located at one end of the continent, hominin paleobiology, and demographic issues (Hosfield and Cole, 2018; 2019, and references therein). In part, as the Barranc de la Boella evidence suggests, it could be the result of a still-deficient record (Key and Ashton, 2022) or a lack of research. In any case, unique findings coming from the interdisciplinary project conducted at Barranc de la Boella gain a particular significance to help understand and even model hominin subsistence and settlement patterns and, in the end, population dynamics during the Early Pleistocene in Western Europe.

6 Conclusion

This article provides detailed information on the large-tool component in Barranc de la Boella, which is highly valuable for any research focusing on the onset of the Acheulean in Europe. Our understanding of how this techno-complex originally dispersed out of Africa and reached Western Europe is dependent on a highly fragmented archaeological and fossil record. In that context, unique sites represent, by definition, isolated evidence. Barranc de la Boella is revealed as a key site in this sense, as it provides the oldest known presence of large shaped tools attributable to the Acheulean in the southwestern end of the continent, in a paleoenvironmentally and archeologically rich context.

The features of the large shaped tools from Barranc de la Boella suggest a technological shift in comparison with the pre-existing Mode 1 type European Early Pleistocene sites, with which this new technology coexists. We documented an initial development of volume management, with a quantitative and qualitative importance of trihedral pick forms, with unifacial and bifacial choppers, cleaver-like forms, and knives as accompanying tool types. These were functional pieces, and it seems clear that there was no need for the makers to produce standardized forms, symmetrical pieces with regular shapes, or full management of bifacial volume. Such systematic bifacial shaping, symmetry, and classic handaxes appear to represent an authentic cultural threshold that develops in more advanced stages of the Acheulean culture. For this reason, Barranc de la Boella must be considered an Early Acheulean site.

Although transitional elements are hard to recognize, as the diagnosis of the Acheulean signature is still strongly based on the presence of certain types of large shaped tools and on a more complex flaking strategy that is sometimes difficult to assess, there is no clear evidence of local evolution that would explain the Barranc de la Boella assemblage. Additionally, it is obvious that site function remains as one of the major drivers of variability in terms of assemblage composition, which hinders the assessment of evolutionary patterns in the fragmented archaeological record for the European late Early Pleistocene.

However, we must seriously consider an Early European Acheulean arriving/developing since that period. In this context, we hypothesize that Barranc de la Boella could reflect a previously unknown dispersal of the Early Acheulean leaving Africa by 1.4 Ma (with the site of 'Ubeidiya as the clearest reference). This would be mirroring the early Acheulean dispersal towards Asia, by means of a spreading through the north Mediterranean coast on the road to Western Europe, at least 1 Ma ago.

Finally, it is worth noting that the ongoing fieldwork and research project at Barranc de la Boella will not only shed light on the dispersal of the Acheulean technology but will also provide valuable paleoenvironmental and behavioral information to make progress in our knowledge of the early human settlement of Europe.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

AO, DL, LA, PG-M, AA, JF-M, and GY: conceptualization, methodology, data curation, formal technological analysis, visualization, and writing; DL and PG-M: 3D scanning and morphometrical analyses; DL, LA, and GY; lithic graphic documentation; JF-M and AO: preliminary use-wear analysis; IC, RH, AP, and PS: taphonomical and zooarchaeological analyses; AG-T, DF, and AR: paleontological and paleoenvironmental analyses; LL-P: conservation and preparation of materials; JV: geoarchaeological analyses; PS and JV: fieldwork direction, data curation, supervision and project management, and funding acquisition. All authors conducted field excavation and contributed to the manuscript revision; AO: final revision and edition. All authors contributed to the article and approved the submitted version.

Funding

The Barranc de la Boella fieldwork was supported by Ajuntament de la Canonja and by Departament de Cultura of Generalitat de Catalunya (CLT009/22/000024). Research was developed within the frame of the projects PID 2021-122355NB-C32 (Spanish MICINN-FEDER), SGR 2021-01239, SGR 2021-01237, and SGR 2021-01238 (Catalan AGAUR), and 2022PFR-URV-64 (URV). Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA) received financial support from the Spanish Ministry of Science and Innovation through the "María de Maeztu" program for Units of Excellence (CEX 2019-000945-M). DL was supported by a postdoctoral Xunta de Galicia grant (ED481B-2022-048). LA was the beneficiary of a H2020-MSCA-IF-2020 grant (101028232). PG-M was supported by a Beatriu de Pinós MSCA-COFUND (AGAUR) (2019 BP 00094). AA was supported by the MICINN "María de Maeztu" excellence accreditation. JF-M was the beneficiary of a post-doctoral contract Margarita Salas from MIU, funded by the Next-Generation EU fund and by "Plan de recuperación, transformación y resiliencia". GY was supported by a MICINN grant (PRE2021-098328). AP was supported by the LATEUROPE (101052653), ERC, and European Union's HORIZON1.1. research program. AR, AG-T, and DF were supported by the Spanish Ministry of Science and Innovation (MICINN/FEDER): PID2021-122356NBI00. DF was supported by the MICINN FPU program (FPU20/03389).

Acknowledgments

The authors are grateful to all the researchers and students involved in the excavation, preparation, and study of the archaeological record from the Barranc de la Boella site. The authors thank Ajuntament de la Canonja and Diputació de Tarragona for their ongoing assistance with the fieldwork, research, and dissemination efforts. The authors also thank J. Oriol Cortés and the Hotel Mas La Boella landowners for their ongoing support of the archaeological project. The photographic recording of the items received essential professional support from Maria D. Guillén. Dr. Eudald Carbonell, the architect of the scientific framework that made the project possible, was instrumental in its inception and has continued to be involved in its progress. The authors also thank Dr. P. Glauberman, who provided language assistance on the first draft of the manuscript. The authors would like to express their gratitude to Drs. M-H Moncel, M. Arzarello, and J. De Vos for inviting them to contribute to the volume "Human Behavior, Cognition, and Environmental Interactions for the Lower Paleolithic." The authors are also grateful to Matthew Caruana and Marcos Terradillos Bernal for their constructive comments, which were extremely helpful when revising the final version of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2023.1188663/full#supplementary-material

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