




The Technological Behaviours of *Homo antecessor*: Core Management and Reduction Intensity at Gran Dolina-TD6.2 (Atapuerca, Spain)

Diego Lombao^{1,2}  · José Ramón Rabuñal^{3,4} · Juan Ignacio Morales^{1,2} · Andreu Ollé^{1,2} · Eudald Carbonell^{1,2} · Marina Mosquera^{1,2}

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Abstract

The ability of early hominins to overcome the constraints imposed by the characteristics of raw materials used for stone tool production is a key topic on the discussion about the evolution of hominin cognitive capabilities and technical behaviours. Thus, technological variability has been the centrepiece on this debate. However, the variability of lithic assemblages cannot be correctly interpreted without understanding site occupational models and function and considering that individual tools represent specific discard moments in a continuous reduction process. In Europe, the earliest technological record is represented by the scarce and scattered Mode 1 technologies, often deriving from occasional occupations or restricted activity areas yielding unrepresentative assemblages. In this paper, we approach the technological behaviours exhibited by Lower Palaeolithic hominins from the subunit TD6.2 of the Gran Dolina site (Atapuerca, Burgos) by including the perspective of reduction intensity studies on the analysis of technological variability. Gran Dolina TD6.2 is a unique and extremely significant archaeological context, as it represents the oldest multi-layered unit of domestic hominin occupations in the Early Pleistocene of Europe. We use the Volumetric Reconstruction Method (VRM) to estimate the original volume of the blanks and quantify the reduction intensity of each core individually to characterise the reduction distribution patterns using Weibull probability distribution functions. Our results suggest differential raw material management in terms of reduction intensity, according to the characteristics of each lithology. This could reflect a solid understanding of raw material qualities and a certain degree of planning. Altogether, the continuity between knapping strategies through reduction denotes constant adaptation to raw material constraints as well as particular knapping conditions, rather than specific compartmentalised mental schemes. In conclusion, *Homo antecessor* toolmakers would have been situational knappers whose technological behaviour would be highly adaptive. This research constitutes the first reduction approach for the European Early Pleistocene assemblages that will lead to a referential framework for other European Early Pleistocene sites.

Extended author information available on the last page of the article

Keywords Reduction intensity · Lithic technology · Cores · Weibull distribution · Technological behaviour · Early Pleistocene

Introduction

The technological variability of Mode 1 lithic assemblages and their significance in terms of behaviour and/or cognitive abilities has been subject of the scientific debate for decades (de la Torre, 2004; Delagnes & Roche, 2005; Kibunjia, 1994; Roche *et al.*, 1999). Different explanations have been proposed to deal with this variability such as functional differences, cognitive abilities, cultural norms, ecological factors, raw material constraints, transport and discard patterns, or even taphonomic factors, among many others (see Toth & Schick, 2018).

Some researchers emphasise the role of the socio-cognitive capacities of early toolmakers, minimising the role of environmental determinism in assemblage variability, while others argue that technological organisation is a behavioural response to specific environmental conditions (see de la Torre & Mora, 2009). However, these apparently dichotomous explanations are somewhat related. Depending on the ability to overcome the limitations of raw material, or whether the adaptation to raw material and/or environmental determinants is “passive” or “active,” the implications in terms of cognitive capacities would be diametrically opposed.

For example, it has been argued that much of the technological variability may actually be the direct consequence of raw material constraints (Delagnes & Roche, 2005; Isaac & Harris, 1997; Stout *et al.*, 2005, 2010). From this perspective, hominins would have found their knapping strategies limited by the properties of the raw materials and, therefore, the characteristics of Mode 1 assemblages would have been determined by raw material features such as size, shape, texture, homogeneity, and workability (Demars, 1982; Luedtke, 1992; Masson, 1981; Primault, 2003; Sieveking & Hart, 1986).

Other authors point out that early hominins were not merely opportunistic stone gatherers (Braun *et al.*, 2009a, b; Harmand, 2009) and that both intra- and inter-assemblage variability can be attributed to behavioural patterns deriving from technological and economic decisions, starting from the raw material selection process (de la Torre, 2004; de la Torre & Mora, 2005; Delagnes & Roche, 2005; Douglass *et al.*, 2018; Gallotti, 2018; Goldman-Neuman & Hovers, 2012; Isaac, 1984; Plummer, 2004; Potts, 1991; Reeves *et al.*, 2021; Roche *et al.*, 2009, 2018; Stout *et al.*, 2005, 2010). Despite accepting that external natural factors such as availability, abundance, or proximity may be influential, it is argued that raw material selection is also governed by knowledge of the qualities of the different rocks and their suitability for knapping. This selection pattern could, therefore, indicate well-developed anticipatory planning and a detailed understanding of fracture mechanics (Braun *et al.*, 2006). Selection patterns linked to raw material properties have been documented as early as 2.6 Ma at sites such as Gona (Stout *et al.*, 2005), or Kanjera South (2 Ma) (Braun *et al.*, 2009a, b; Douglass *et al.*, 2018; Plummer, 2004; Reeves *et al.*, 2021).

This debate involves not only raw material selection but also the variability of reduction strategies. Some authors have suggested that the *ideational know-how* in Oldowan toolmakers would be rudimentary, so the assemblage's variability could be explained by the performance of some simple actions, involving elementary reduction sequences (Pelegriin, 1993). However, most studies do agree that a certain level of technological complexity is demonstrated during Mode 1, implying that early toolmakers would have had the manual precision and technical skills required to manage the challenges of the available raw materials given their specific needs (de la Torre, 2004; de la Torre & Mora, 2018; Delagnes & Roche, 2005; Semaw, 2000).

Given the magnitude of the implications of this debate, numerous studies have focused on the relationship between lithic variability in Early Stone Age assemblages and raw material constraints, stone tool transport, and land use, especially in East African Oldowan research (Blumenschine *et al.*, 2012; Braun *et al.*, 2009a; Douglass *et al.*, 2018; Isaac, 1977, 1981; Potts, 1989, 1991; Potts *et al.*, 1999; Reeves *et al.*, 2021).

The theoretical orientation of these studies often influences the methods used (de la Torre & Mora, 2009). Thus, ecological perspectives tend to focus exclusively on the quantification of artefact variability, paying little attention to the specific knapping methods, whereas socio-cognitive frameworks tend to prefer in-depth descriptions of the core reduction strategies (de la Torre, 2004, 2009; Delagnes & Roche, 2005; Roche *et al.*, 1999; Texier, 1995). However, few have attempted to integrate quantitative and qualitative perspectives (but see Cueva-Temprana *et al.*, 2022; Potts, 1991; Reeves *et al.*, 2021).

The main aim of socio-cognitive approaches is to reconstruct the *chaînes opératoires* of lithic assemblages in order to understand the knapping techniques and reduction sequences, making possible the evaluation of the cognitive skills required (de la Torre & Mora, 2009). In these studies, the analysis of core reduction strategies is a fundamental area of research since it allows to infer the technological behaviour and cognitive capacities of toolmaking hominins.

However, any lithic assemblage comprises individual elements involved in a dynamic transformation process driven by the morpho-volumetric changes resulting from use and re-use, rejuvenation or breakage at the time they became part of the archaeological record (Davidson, 2002). In this way, archaeological stone tools represent specific moments in a continuous sequence of reduction (Shott, 2003), and some of the visible attributes are closely related to their life history (Schiffer, 1987) and degree of curation (Shott, 1989, 1996). The archaeological record is the static material manifestation of dynamic behavioural and geomorphological processes (Binford, 1979, 1980; Schiffer, 1975, 1987); for this reason, different reduction intensities may illustrate varying behavioural responses to the conditions of lithic production (Marwick, 2008), including raw material availability and proximity, tool function, duration of occupational events, and other aspects. Thus, the distribution of the different reduction intensities within an assemblage may provide information about planning, land use, transport, settlement patterns, and subsistence strategies (Andrefsky, 1994; Kuhn, 1991; Nelson, 1991; Schiffer, 1975; Shott, 1989; Shott & Sillitoe, 2004; Varien & Potter, 1997).

Reduction intensity also has implications beyond the rate of artefact accumulation (Schiffer, 1987), for example the morphological variability of tools (Dibble, 1987, 1995a; Jelinek, 1976; Morales *et al.*, 2015), cores (Dibble, 1995b), and core tools (McPherron, 1999). Each core recovered in the archaeological record presents a set of technical features corresponding to the moment in the reduction continuum in which it was discarded. Varying the discarding time could result in the manifestation of a different set of features which could lead to infer a different exploitation system (Guilbaud, 1995). For these reasons, reduction intensity and its distribution in the assemblage may significantly affect the presence or absence of specific “core types” (Potts, 1991; Reeves *et al.*, 2021).

There is scant research on the distribution patterns of reduction intensity in core assemblages, (Douglass *et al.*, 2018), especially compared to the abundant literature on retouched tools (*i.e.* Morales, 2016; Shott, 2002; Shott & Seeman, 2015; Shott & Sillitoe, 2004, 2005). Moreover, the relationship between reduction intensity and reduction strategies can provide much more information about technological behaviours than the simple classification of the different knapping strategies or methods. Classificatory approaches are necessary to the extent that we inherently need some kind of sorting and discretisation, although this approach often results in watertight compartmentalisations in which each reduction strategy identified is often argued to correspond to a predefined and independent mental template. These templates, however, are strongly dependent on external factors, such as raw material constraints, so strategy changes can take place during a single knapping sequence, meaning, therefore, that a priori independent knapping strategies can actually be closely related to one another (Guilbaud, 1995). For these reasons, this variability in reduction strategies cannot be fully understood without (1) considering the specific moment in the reduction sequence represented by each core and, (2) its relationship with the rest of the cores in the assemblage.

To approximate the first aspect, it is necessary to quantify the reduction intensity of each core and understand the volume removed during the knapping process. By doing this, it may be possible to quantitatively define the precise moment throughout the reduction continuum represented by each core and its associated technical features. With regard to the second aspect, Guilbaud (1995) defined the concept of “*champ opératoire*”, or operatory field, which is a conceptual approach to the reduction process based on the premise that knapping sequences do not follow linear independent trajectories with a pre-established objective from the first strike of the core to the last blank detachment. As reduction advances, changes in strategy can result from multiple causes, including morpho-volumetric changes in the cores, raw material heterogeneity, and knapping errors. This perspective has explicitly been applied to European Middle and Upper Palaeolithic contexts (de Lombera-Hermida *et al.*, 2011; García-Catalán *et al.*, 2013; Morales *et al.*, 2013; Rabuñal, 2016; Vaquero, 1999, 2011) and is a useful tool for analysing the interrelationships of the different knapping strategies in older chronologies.

For these reasons, we analyse the variability in technological behaviour of *Homo antecessor*, by studying the cores recovered from Lower Palaeolithic subunit TD6.2 of the Gran Dolina site, combining both technological (qualitative) and reduction intensity (quantitative) approaches. The aims of this work are (1) to evaluate the

behavioural responses of these hominins to the ecological features of the environment such as the raw material characteristics and (2) to define the flexible or watertight nature of the dynamics of exploitation that they developed. For this purpose, we explore all the stages of the reduction sequence, from the raw material selection strategies based on the estimation of the original volume of the blanks, as well as the analysis of the reduction strategies and the operatory field, to the reduction degree of the cores at the discard moment.

Materials and Methods

Archaeological Site

Gran Dolina is a cave site located in the Trinchera del Ferrocarril complex of the Sierra de Atapuerca (Burgos, Spain), involving a 25-m sedimentary sequence in which 12 lithostratigraphic units have been identified (TD1-TD11 from bottom to top) (Campaña *et al.*, 2016a; Gil *et al.*, 1987; Parés & Pérez-González, 1999; Parés *et al.*, 2018; Pérez-González *et al.*, 2001).

To date, there have been two phases of excavation in Unit TD6: between 1994 and 1997, in an area of about 8 m² through a test pit in the southern area of the site; and from 2003 to 2011, in an area of 13 m² in the western and central sectors of the Gran Dolina section. These *ca.* 20m² of discontinuous extension have provided more than 9000 faunal remains, 170 human remains attributed to *Homo antecessor*, and 1046 lithic remains, among others (Allué *et al.*, 2015; Mosquera *et al.*, 2018; Saladié *et al.*, 2011, 2014).

Consistent magnetostratigraphic (Parés & Pérez-González, 1995, 1999) and US-ESR dating (Duval *et al.*, 2012; Falguères *et al.*, 1999) places the formation of TD6 below the Brunhes-Matuyama boundary with a numerical estimation older than 780 ka, while thermoluminescence (Berger *et al.*, 2008) and direct ESR on human remains (Duval *et al.*, 2018) have provided ranges of 960 ± 120 ka and 772–949 ka, respectively. Unit TD6 is a 3-m-thick sedimentary formation divided into three subunits, from bottom to top: TD6.3, TD6.2, and TD6.1, TD6.2 being the richest archaeo-palaeontological subunit.

More than 800 lithic remains, including 50 cores, and over 6000 faunal remains have been recovered from subunit TD6.2, in addition to 165 human remains attributed to *Homo antecessor* (Bermúdez de Castro *et al.*, 1997, 1999; Carbonell *et al.*, 2005). Multidisciplinary works have interpreted TD6.2 as a residential camp (Carbonell *et al.*, 1999; Díez *et al.*, 1999; Mosquera *et al.*, 2018; Saladié *et al.*, 2014, 2011, 2021), where complex behavioural dynamics have been documented, from the identification of cannibalistic practices to the hunting and selective transport of large ungulates, food sharing and social cooperation (Fernández-Jalvo *et al.*, 1996; Saladié *et al.*, 2011, 2014).

Recently, a study based on the sedimentology of the site has proposed that the archaeological remains would be in a secondary position, as they would have accumulated in the cave by geological processes related to a channel and debris flows

(Campaña *et al.*, 2016b), which certainly may question some of the behavioural inferences made from this assemblage.

However, previous taphonomic works (Saladié *et al.*, 2011, 2014) suggest that these archaeological remains are not affected by post-depositional processes and that the accumulation of these remains is mainly a product of anthropogenic activity. On the other hand, technological studies (Mosquera *et al.*, 2018) show that the operative chains of all raw materials are complete, which, together with the presence of refits, would indicate a primary position of these remains. In addition, more recent studies analysing the anisotropy of magnetic susceptibility (AMS) (Parés *et al.*, 2020) point to a very low-energy hydrodynamic sedimentation regime, with no signs of post-depositional disturbance or massive transport. In addition to these studies, Saladié and colleagues (Saladié *et al.*, 2021), based on the spatial co-dependence between lithic tools and osteological remains, proposed an undisturbed character or the remains of TD6.2. In sum, despite the Campaña *et al.* (2016b) arguments, the multidisciplinary evidence supports the primary position of the archaeological remains.

In this study, we have followed the internal archaeo-stratigraphic division of TD6.2 proposed by Mosquera and colleagues (Mosquera *et al.*, 2018), based on the sedimentary facies described in Campaña and colleagues (Campaña *et al.*, 2016a, b), and grouped the remains into three archaeo-stratigraphic layers according to their vertical distributions: TD6.2.4, TD6.2.2–3, and TD6.2.0–1 from base to top (Fig. 1).

Raw Materials

A total of five different lithological groups have been identified in the TD6.2 assemblages, all coming from sources 1–3 km approx. away from Gran Dolina (García-Antón, 2016; Ollé *et al.*, 2013): sandstone, quartzite, chert, quartz, and limestone.

- The group generically labelled as sandstone includes sandstone, metasandstone, and schist. They are soft materials with a homogeneous structure and fine to medium-sized grain. The cobbles are of small-medium size, with a morphology ranging from rounded to subflat. Their workability is moderate with a considerable number of fissures that determine the knapping processes. Regarding the accessibility, they can be found in abundance very close to the site, from 1 km away (Ollé *et al.*, 2013; Terradillos-Bernal & Rodríguez-Álvarez, 2014).
- The quartzite group includes orthoquartzite, metaquartzite, and quartzarenite. In other works (Mosquera *et al.*, 2018), quartzarenite has been considered a separated group, but here, we have included it in the quartzite group given its low representation. It is abundant in fluvial terraces and colluviums, at distances between 1 to 3 km, presenting small and medium sizes, with rounded subspherical morphologies. The workability ranges from moderate to good, depending especially on the grain size—which oscillates from fine to medium—and the homogeneity of the internal structure (Ollé *et al.*, 2013; Pedergrana *et al.*, 2017; Terradillos-Bernal & Rodríguez-Álvarez, 2014).

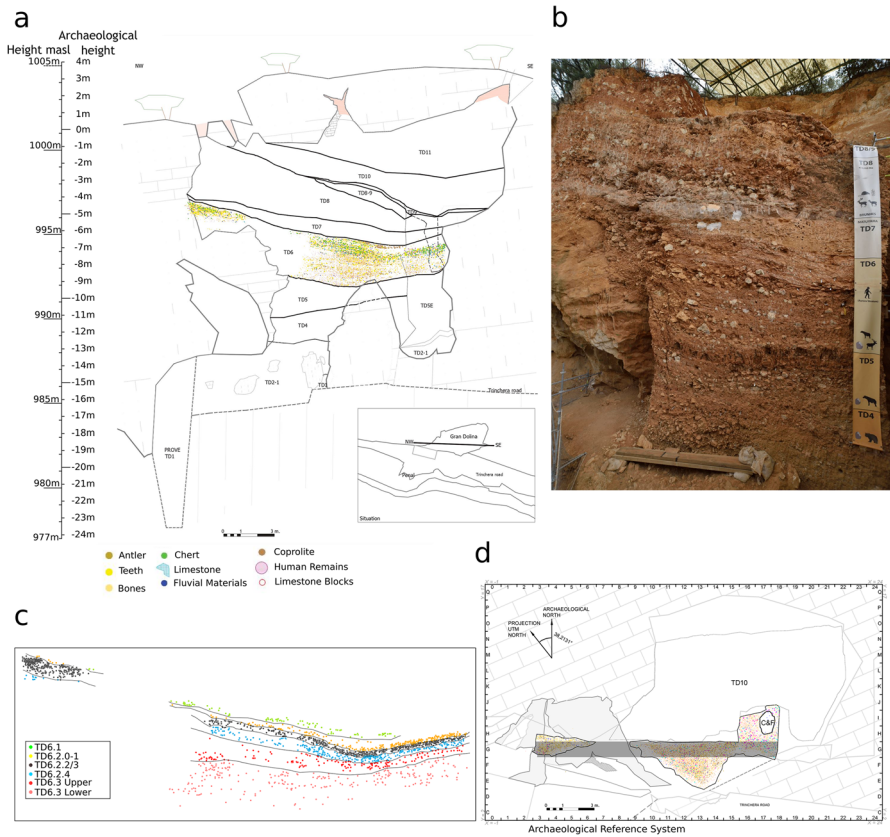


Fig. 1 **a** Stratigraphic section of Gran Dolina site (R. Pérez) and vertical distribution of the TD6 archaeological remains excavated up to date (M. Mosquera). **b** Stratigraphic section (Photo: A. Oillé). **c** Vertical distribution of subunits of TD6 in row G, in the contacts of rows G and H (M. Mosquera); **d** Horizontal plan of the Gran Dolina site, with the spatial distribution of the TD6 archaeo-paleontological remains excavated to date (the grey zone indicates the section represented in (c)) (Modified from Mosquera *et al.*, 2018)

- Quartz appears less abundantly in the form of pebbles and small cobbles, at distances of 1 to 3 km from the site. Morphologies tend to be rounded and well-rounded sub-spherical, with medium-size grain and irregularities and fissures that lead to fractured flakes, limiting their workability (Terradillos-Bernal & Rodríguez-Álvarez, 2014, 2017).
- The chert group comprises Neogene and Cretaceous varieties:
 - Late Miocene (Neogene) chert is abundant in the surroundings of the Sierra de Atapuerca, appearing as large to very large blocks (up to 1 m) and angular fragments with textural and quality irregularities. These irregularities occur in each block: the outer surfaces have a finer and more homogeneous structure, while the inner parts are usually coarse-grained with abundant geodes (Soto *et al.*, 2021). The relative softness of this material means that it is not necessary to apply much

force during the knapping process, so its workability can range between moderate and high. Its abundance and easy access make it the most frequent raw material in the Gran Dolina archaeological record (Ollé *et al.*, 2013). Often, tools made on Neogene chert are strongly affected by diagenetic alteration, preventing functional or technological analysis in many cases.

- Turonian-Santonian (Cretaceous) chert appears in two different sources very close to the archaeological sites of Trinchera del Ferrocarril (about 1 km):

The first area is located in Rasa de San Vicente, towards the SSE limit of the Sierra. It is a fossiliferous chert with a microcrystalline wackestone structure. The average size of the nodules is 20 cm in diameter (ranging from 10–30 cm). It has poorer quality than the next.

The second outcrop is located near Valdecuende, in the central area of the Sierra de Atapuerca. The irregular oval-shaped nodules rarely exceed 10 cm in diameter (ranging from 5 to 15 cm), with less fossil presence and a compact siliceous mudstone texture.

Cretaceous chert has a medium to high suitability for knapping due to its microcrystalline wackestone structure, but its workability is limited by its small size, its polyhedral and thick shape in the case of the Valdecuende variety, and the presence of some irregularities and fissures in both varieties (Terradillos-Bernal & Rodríguez-Álvarez, 2014).

- Finally, limestone originates from the karstic Cretaceous substratum of the Sierra de Atapuerca itself.

Methods

Core Attributes

For the technological analysis, we based our approach on the Logic Analytical System (Carbonell *et al.*, 1983, 1992; Rodríguez-Álvarez, 2004) complemented with some additional attributes. Following the protocol proposed by Vaquero (1997, 2004), the technical analysis of the cores has been carried out at two scales: at a general level, understanding the core as a whole and analysing the spatial and technical relationships between all the surfaces; and at an elementary level, analysing each surface individually. Core fragments and cores that were severely altered and poorly preserved ($n=3$) were excluded from the analysis.

Different volumetric structures of exploitation (VSE) have been defined according to a series of morpho-technical characteristics, such as the number and relationship of flaking and percussion surfaces, type and length of the flaking surfaces, and general polarity of the removals (Fig. 2). However, the importance of each characteristic in the definition of the VSE varies according to the number of exploitation surfaces. Thus, for unifacial cores, the general polarity articulates the division between different VSEs, while for bifacial cores, it is the relationship between the flaking surfaces that most characterises them.

Besides, we have also considered some quantitative attributes such as the angle between percussion and flaking surfaces, as well as the percentage of non-cortical

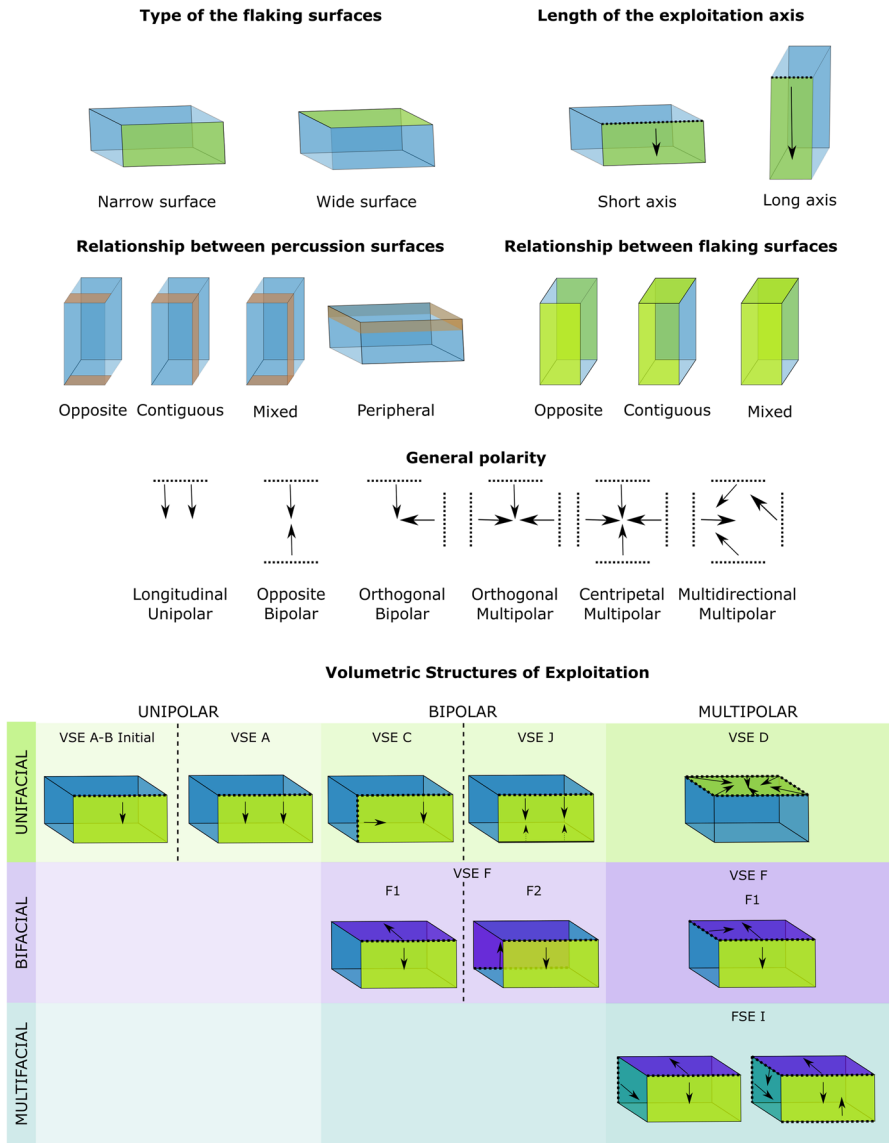


Fig. 2 Morpho-technical attributes analysed and volumetric structures of exploitation (VSE). Note the absence of B, E, G, H VSEs, these are theoretical models not represented as they are not documented in TD6.2 subunit

surface, used elsewhere as a proxy of the reduction intensity (Douglass *et al.*, 2018; Li *et al.*, 2015; Lombao *et al.*, 2019). 3D models of the cores have been used to quantify the Scar Pattern Index (SPI), proposed by Clarkson and colleagues (Clarkson *et al.*, 2006), by computing the vectors established by the initial and final coordinates of each removal. SPI values, ranging from 0 to 1, were obtained by dividing the norm of the vector resulting from the addition of all the vectors, by the sum of

the norms of all the vectors (Bretzke & Conard, 2012; Clarkson *et al.*, 2006). Values close to 0 are related to opposing scar patterns, as in the case of opposite bipolar strategies; while values close to 1 mean that the vectors run parallel to each other, as in longitudinal unipolar strategies.

The 3D models of the cores were obtained using both a Breuckmann SmartScan HE with a 250-mm field of view and structure-from-motion techniques following Porter and colleagues' workflow (Porter *et al.*, 2016). These models are available for scientific and/or academic purposes at <https://doi.org/10.5281/zenodo.4680626> (Lombao *et al.*, 2021).

Reduction Intensity

Given the ellipsoid-like morphologies of the Cretaceous chert nodules as well as the quartzite, sandstone, and quartz cobbles, we applied the Volumetric Reconstruction Method (VRM) (Lombao *et al.*, 2020) to estimate the original size of the blanks and the core reduction intensity. As already mentioned, Neogene chert is found as large blocks with a great morphological diversity (Ollé *et al.*, 2013), and in many cases, the only way to handle this lithology is by striking these blocks to obtain large flakes or fragments to be used as cores. Since the VRM has not been tested in cores on flake, Neogene chert was not included in the VRM analysis.

The diacritical analysis of the cores was used to estimate the number of flaking generations on the maximum core axes and to define the number of corrections to be applied to each maximum dimension. When n flaking generations were identified along the maximum length and width, n times the platform thickness mean from the assemblage's flakes was added to the dimension. For the maximum thickness, the mean flake thickness was used. The median was used instead of the mean when the distribution of the measured flake thickness or platform thickness was non-parametric. This was calculated independently for each layer and raw material type material (see Supplementary Table S1). Finally, the corrected dimensions of each core were used to compute the ellipsoid volume formula and estimate the original volume of the blanks.

To estimate the reduction intensity, first, the volume measured through the 3D models of the core was divided by the estimated volume of the original blank and multiplied by 100, obtaining the percentage of the remaining volume. Then, the percentage of extracted volume was calculated by subtracting this value from 100. The volume in cubic centimetre was the chosen measuring unit instead of the mass in grammes to avoid discordances generated by the different densities of each raw material.

Weibull Distributions

The estimated reduction intensities of the cores were interpreted in terms of survivorship prior to abandonment. Weibull distributions are used to model failure in relation to time, generating probability density functions (pdf), so we used them to model the abandonment ratio of the assemblage.

The pdf of a distribution is defined using the shape (β) and scale (α) parameters. Here, α represents the point at which 63.2% of the sample has failed (meaning, 63.2% of the cores were discarded) (Dorner, 1999), while β defines the shape of the hazard function of the distribution, so that different values in β produce different slopes on a probability plot. Shott (Shott, 2002; Shott & Sillitoe, 2004) defined three general survivorship curves: (i) Type I or attritional curves, where the discard ratio increases as reduction advances; (ii) Type II or random curves, where the failure risk is constant over time; and (iii) Type III or early refusal curves, where the failure risks decrease with time.

Statistical Analysis

Different statistical analyses were carried out to investigate two main questions: to test whether there are differences in the management of the different raw materials (in terms of selection, knapping strategies, and reduction intensity) and to evaluate the diachronic evolution of these aspects throughout the TD6.2 subunit.

The Shapiro–Wilk (S-W) test was applied to assess the normal distribution of the data. Given the low sample sizes and the nonparametric distributions of most of the variables (Supplementary Tables S2–S7), nonparametric tests were used thereafter.

To test for differences in the raw material selection according to blank size and reduction intensity, we performed Mann–Whitney U (M-W) or Kruskal–Wallis (K-W) and post hoc pairwise Dunn’s test with Holm adjustment (Holm, 1979), in order to compare the central tendencies of different variables, such as core volumes or percentage of extracted volume.

This analysis was not limited to the study of the central values, but we also explored their distributions by raw materials. For that, we applied the Kolmogorov–Smirnov test (K-S) to observe the degree of variability in the volume of the blanks selected, the volume of the cores once they were discarded, and the percentage of extracted volume. This procedure was also applied to compare the reduction intensity by layers.

In addition, we applied Weibull distributions to explore differences in discard patterns between raw materials and between layers. The Weibull distributions were calculated with the maximum likelihood estimation method using the “fitdistr” function provided by the “fitdistrplus” (Delignette-Muller & Dutang, 2015). Following the procedures of Douglass & colleagues (Douglass *et al.*, 2018), a dummy case with a 100% extracted volume was added prior to fitting the survivorship curves to make the Weibull distributions comparable.

Also, we have applied correlations following Kendall’s Tau method to evaluate the relationship between the reduction intensity and different parameters, such as the percentage of non-cortical surface area or the estimated original volume of cores.

Lastly, the chi-square test has been used to assess the differences in the frequency of VSE by layers and by raw materials. The differences observed at a qualitative level have been contrasted from a quantitative point of view through the comparison of SPI values (Clarkson *et al.*, 2006) at the three layers.

Scripts and steps that followed are described in the Supplementary Material.

Fig. 3 Cores recovered in TD6.2. **a** ATA11 TD6.2 G04 41 (Quartzite, VSE A). **b** ATA03 TD6.2 G15 35 (Quartzarenite, VSE A). **c** ATA07 TD6.2 F12 147 (Quartzite, VSE A). **d** ATA07 TD6.2 F12 85 (Quartzite, VSE A). **e** ATA08 TD6.2 F12 32 (Quartzite, VSE A). **f** ATA07 TD6.2 G11 122 (Quartzarenite, VSE C). **g** ATA96 TD6.2 H17 233 (Quartzite, VSE F-2). **h** ATA94 TD6.2 G17 2 (Sandstone, Chopper-core). **i** ATA07 TD6.2 G10 73 (Quartzite, VSE F-1). **j** ATA06 TD6.2 G13 47 (Sandstone, VSE F-1)

Results

Volumetric Structures of Exploitation

The analysis of cores and tools produced on cobbles identified seven volumetric structures of exploitation (VSE) (see Fig. 2):

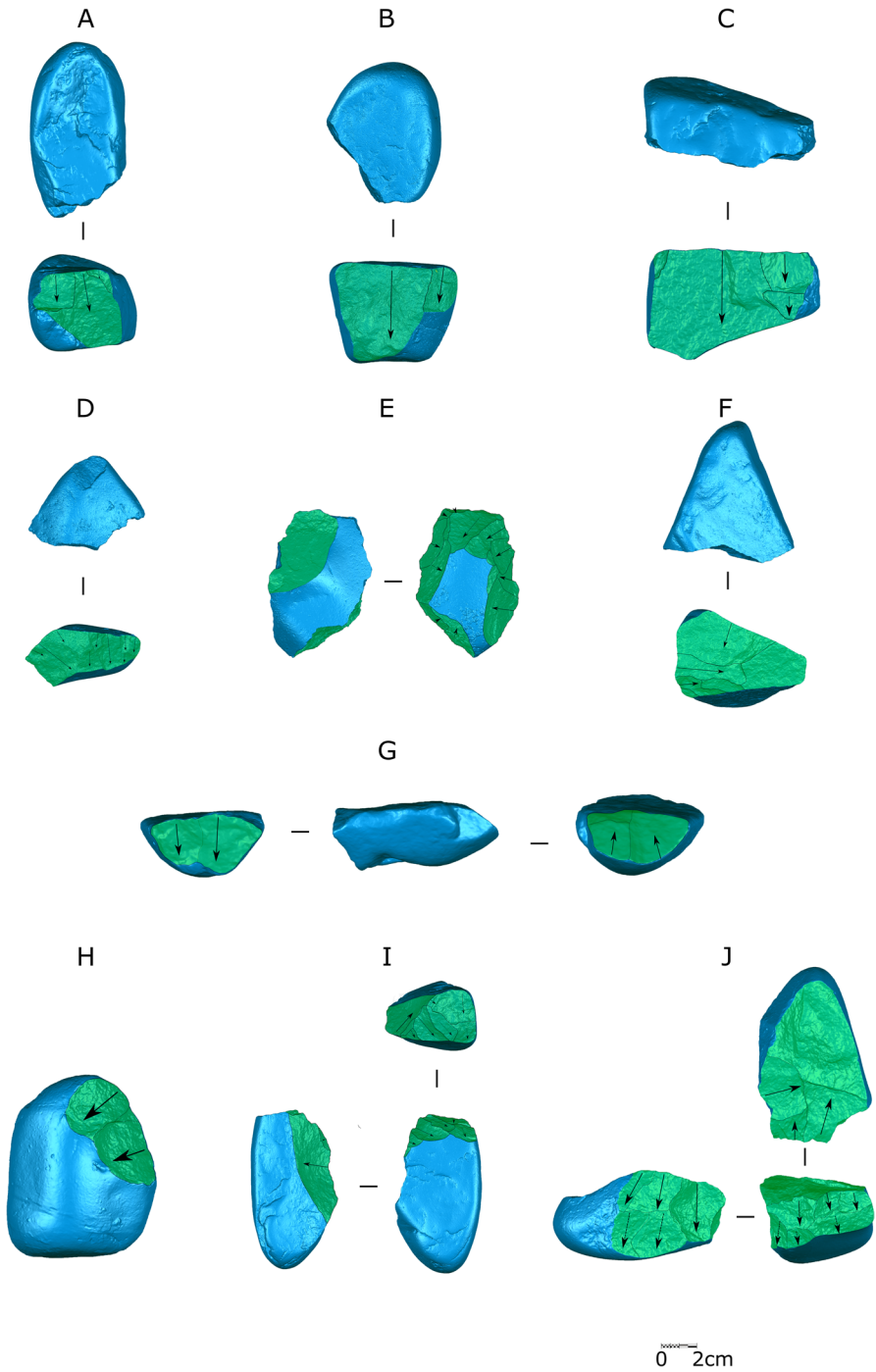
VSE A-B-Initial ($n=6$) Cores with few isolated removals, and therefore without a well-defined volumetric structure, resulting from testing or the occasional flaking of a blank. Four cores show a very short sequence of unipolar longitudinal removals on one surface, one has only two isolated removals, and one presents a sequence of three alternating removals.

VSE A Unipolar longitudinal on narrow surface ($n=11$): The exploitation was focused on a narrow surface and is articulated through a single percussion platform and following the same longitudinal axis. Abrupt and semi-abrupt angles ($75\text{--}90^\circ$) between the exploitation and percussion surfaces predominate. VSE A may present more extensive perimetral/peripheral flaking development in advanced reduction stages. In these cases, the transversal and sagittal planes are exploited uniaxially through the rotation of the horizontal plane, leading to a centro-polarised or semi-tournant trend (Fig. 3e).

VSE C Unifacial bipolar ($n=1$): The exploitation was developed on a single surface of the core articulated from two contiguous percussion platforms, leading to an orthogonal bipolar unifacial structure. A narrow face was first exploited longitudinally, following the short axis of the exploitation surface; the core was then rotated, and the same surface was exploited following the long axis (Fig. 3f).

VSE D Unifacial (or bifacial) multipolar centripetal ($n=5$): Flakes were removed from platforms extending along the edge of the core without a specific recurrent starting point and oriented towards the centre of the core. In some cases, the exploitation was bifacial, but the centripetal pattern is only seen on one face, while on the other face there is only evidence of limited unipolar longitudinal flaking generated either prior to or after the centripetal exploitation (Fig. 4c, e).

VSE F Bifacial bipolar/multipolar exploitation ($n=8$): Cores with two flaking surfaces, either adjacent or opposite, involving two independent longitudinal unipolar flaking series. Depending on the spatial relationship between the exploitation and percussion surfaces, it was possible to differentiate two variants:



– VSE F1 ($n=6$): The exploitation was organised around two contiguous surfaces

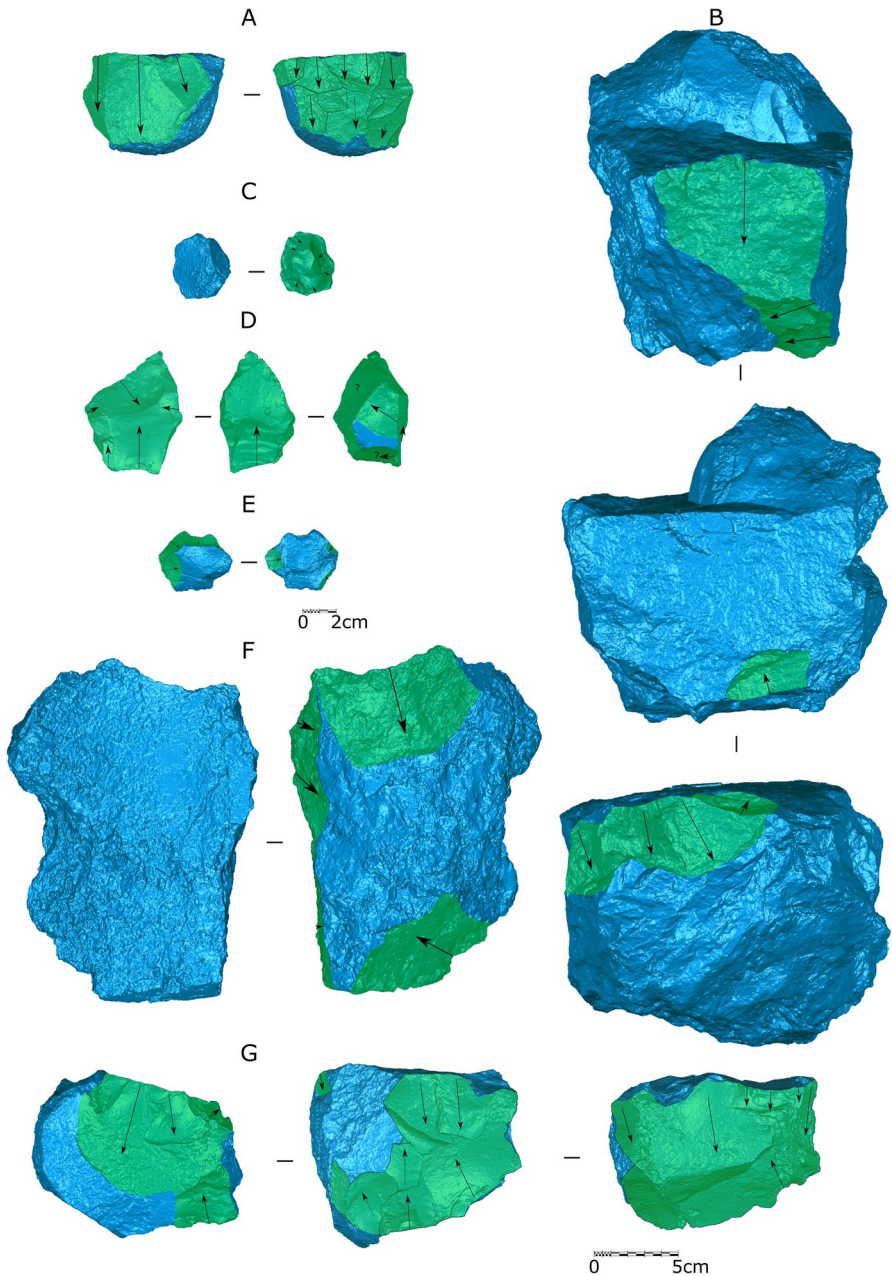


Fig. 4 Cores recovered in TD6.2. **a** ATA05 TD6.2 G15 50 (Neogene chert, VSE A). **b** ATA07 TD6.2 G10 97 (Neogene chert, VSE F). **c** ATA04 TD6.2 F14 96 (Cretaceous chert, VSE D). **d** ATA09 TD6.2 F13 526 (Cretaceous chert, VSE I). **e** ATA08 TD6.2 F12 59 (Cretaceous chert, VSE D). **f** ATA07 TD6.2 F12 93 (Neogene chert, VSE A). **g** ATA02 TD6.2 G04 1 (Neogene chert, VSE I)

from two percussion platforms that were also contiguous. They therefore have two longitudinal unipolar series on two adjacent faces, usually generating a general orthogonal bipolar scheme (Fig. 3i). Bifacial cores presenting an orthogonal or opposite bipolar exploitation on one surface and a longitudinal unipolar series on the adjacent face are also included here since two contiguous surfaces were exploited, although with a generally orthogonal multipolar scheme (Figs. 3j and 4b). In some cases, an incipient facial hierarchisation was observed (Fig. 3i).

- VSE F2 ($n=2$): Cores with two opposite or contiguous faces exploited in a unipolar longitudinal way from two opposite platforms generating opposite bipolar schemes. The two flaking surfaces are not related to each other and display two independent longitudinal unipolar series (Fig. 3g).

VSE I Trifacial/multifacial multipolar exploitation ($n=10$): Cores with at least three flaking surfaces and an independent series of removals produced from three or more percussion platforms. These may be either the consequence of the final reduction stages or the application of multiple series of a few longitudinal unipolar extractions on each face with no well-defined scheme and generating irregular shapes. Abrupt and semi-abrupt angles between the percussion platforms and the exploitation faces predominate.

VSE J Bipolar-on-anvil technique ($n=3$): Cores exploited following the bipolar-on-anvil technique where the exploitation was carried out from the horizontal or vertical axis, following the scheme proposed by de Lomberra and colleagues (de Lomberra-Hermida *et al.*, 2016). In two cases, the exploitation was limited to a single surface, while on one core this was expanded to the two adjacent faces with the first being used as a percussion platform.

Tools on cobbles ($n=3$) Unifacial chopper-like cores presenting few extractions and a “cutting edge” covering around 20–25% of the perimeter. Two chopper-cores of sandstone and limestone were recovered from TD6.2.0–1, and a quartzite example was found in TD6.2.4.

The relationship between the core volumes at the time of discard and the volumetric structures shows that cores with a lower remnant volume correspond to VSE D and J, with VSE I presenting the largest proportions of remnant volume. This pattern is maintained when comparing the original estimated volumes, where the original blanks of VSE D and J are smaller and more homogeneous (Fig. 5a). On the other hand, in VSE A and F there is greater variability in the original blanks, although these do tend to be larger. Thus, a two-fold pattern arises from the correlation between the VSE and reduction stages. VSE D, I, and J are identified within the more reduced cores, while VSE A, F, and C are found within those in early-intermediate reduction stages (Fig. 5b).

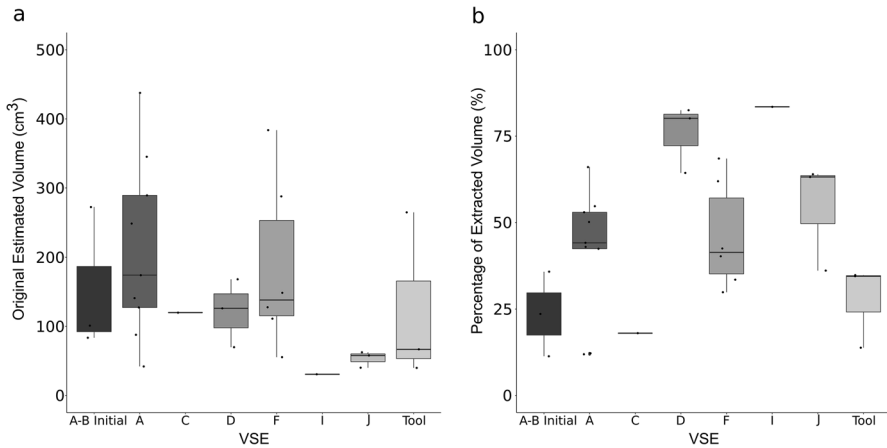


Fig. 5 **a** Boxplot of the estimated original volumes. **b** Boxplot of the percentage of estimated extracted volume according to volumetric structures of exploitation (reduction strategies)

Raw Material Management Variability

There are clear differences in the VSEs both in their distribution by raw material ($X^2 = 77.74$, $df = 35$, $p < 0.001$) (Fig. 6c), as well as in the technological characteristics depending on the raw material.

Sandstone is exclusively exploited using unipolar longitudinal systems either through one or two flaking surfaces (VSE A and VSE F1). The exploitation follows the short axis of the flaking surface, generating short products, and flat wide cortical surfaces were frequently used as percussion platforms (Fig. 3a–d).

This pattern is similar in quartzite, where unifacial longitudinal unipolar strategies predominate, followed by bifacial strategies (VSE F), while there is a scarce representation of VSE A-B, orthogonal unifacial (VSE C), and centripetal unifacial (VSE D).

Unlike quartzite and sandstone, in Neogene chert cores, mainly non-cortical surfaces are used as percussion platforms (Fig. 4a). There is a predominance of multipolar multifacial strategies (VSE I), in which after a short series of removals the core was rotated to find a new suitable percussion platform, generating abrupt angles between surfaces and a marked orthogonal character (Fig. 4g).

In Cretaceous chert cores, a high percentage of centripetal strategies (VSE D) stands out, using both nodules and flakes as blanks. In the cores-on-flakes, the ventral surface was used as a percussion platform. The VSE F and VSE I are also present, but, due to the small size of the cores, there was generally a change of percussion platform and/or flaking surface after each removal (Fig. 4d).

Quartz cores are mainly reduced following the bipolar-on-anvil technique (VSE J). Finally, limestone presents no preferential exploitation system.

There are no statistically significant differences between the final volume of the cores-on-flake and those from cobbles or nodules (M-W $p = 0.43$), due to the use of

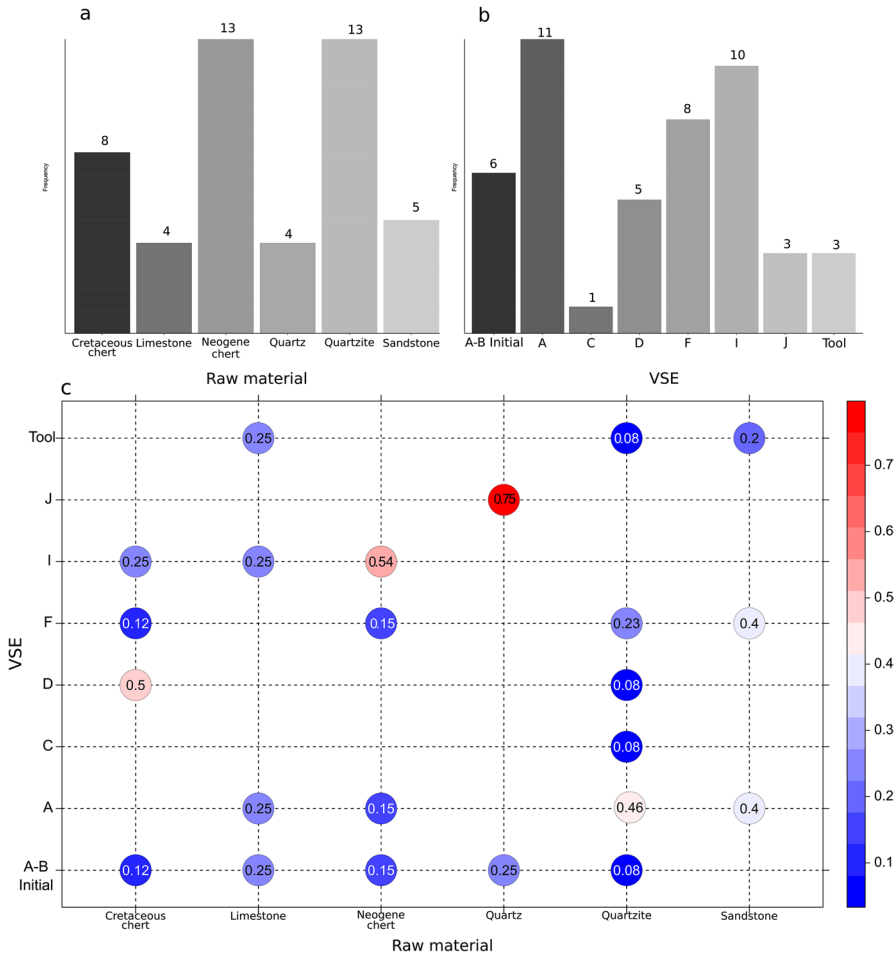


Fig. 6 **a** Bar chart of frequencies of raw material cores. **b** Bar chart of frequencies of VSE cores. **c** Bubble grid chart showing the VSE distribution according to each raw material. In **(a)** and **(b)**, the numbers in the graphs refer to total count; in **(c)**, the numbers reflect the percentage

relatively large flakes as cores, mainly in Neogene chert, although the use of smaller flakes of other raw materials, especially Cretaceous chert, was also documented. There is a great variability in the final volumes of Neogene chert ($SD=616.65$; $CV=118.99$), which may be related to different degrees of reduction or to greater heterogeneity of the original blanks. The presence of two large cores of Neogene chert is remarkable and may suggest that many of these cores are not volumetrically exhausted (Fig. 7).

Conversely, the results indicate that there are two different groups of raw materials regarding the final core volumes: (1) quartz and Cretaceous chert present smaller volumes, while (2) Neogene chert, quartzite, limestone, and sandstone are larger. This tendency is maintained when comparing the estimated original volume through

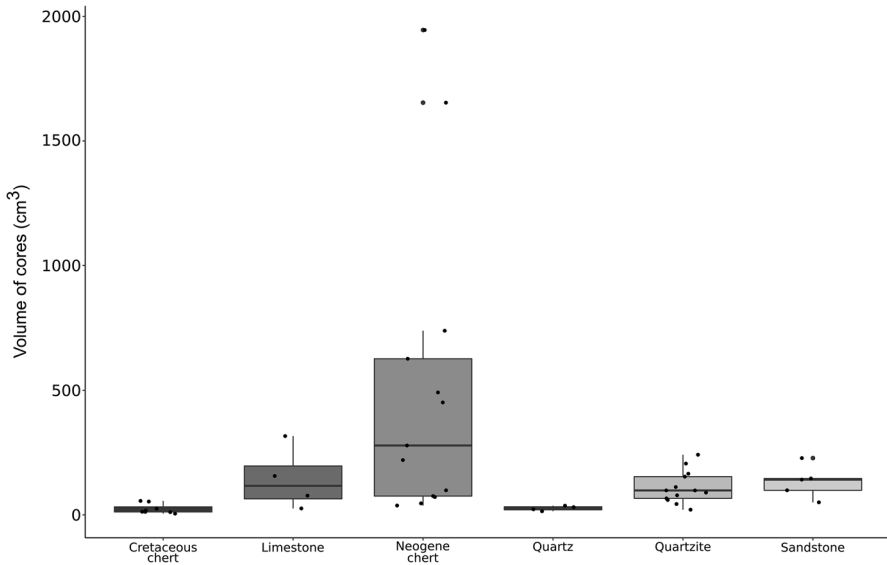


Fig. 7 Volume of discarded cores (cm^3) recovered in TD6.2 according to raw material type

the VRM, in such a way that quartzite, limestone, and sandstone present larger average values, while quartz and Cretaceous chert have smaller estimated volumes (see Fig. 8). The Kolmogorov–Smirnov test comparing the distribution of the estimated original volumes according to raw material shows statistically significant differences in the distribution of values between quartz and both sandstone and quartzite, as

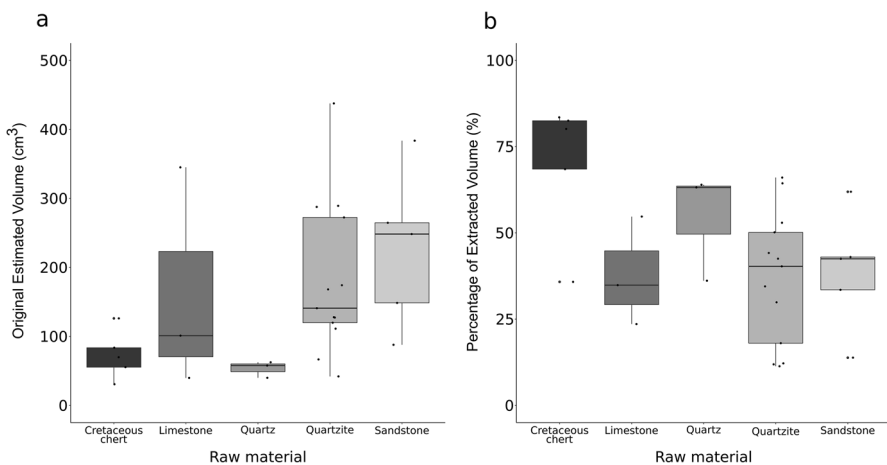


Fig. 8 **a** Boxplot of the estimated original volumes. **b** Boxplot of the percentage of estimated extracted volume according to raw material type. Neogene chert is excluded from VRM analysis

well as between Cretaceous chert and quartzite (see Supplementary Tables S8-S9), thus differentiating the smallest raw materials (quartz and Cretaceous chert) from quartzite and sandstone.

Interestingly, these differences in sizes and volumes are maintained in the reduction intensity. Sandstone and quartzite present the lowest Weibull β and α values, while quartz and Cretaceous chert show the highest (Table 1). Thus, Cretaceous chert is the most reduced raw material, followed by quartz, while sandstone, limestone, and quartzite are the least reduced. Even though these differences are only statistically significant between the Cretaceous chert and quartzite (K-S (p)=0.007) (Supplementary Table S10), the observed pattern suggests a differential raw material management.

To evaluate whether these differences are in line with other reduction intensity proxies, the percentage of extracted volume was compared with the percentage of non-cortical surface. The results indicate a strong correlation between the two variables (Kendall's tau=0.66, $r^2=0.68$, $p<0.001$). Conversely, there is no correlation between the estimated original volume of the cores and the degree of reduction (Kendall's tau = -0.13, $p=0.32$), evidencing that the VRM is not biased by the size of the core. Finally, there is a high correlation between the estimated volume of the blanks and the final volume of the cores (Kendall's tau=0.71, $p<0.001$). However, there are significant differences depending on the raw material. The correlation is moderate for quartzites (Kendall's tau=0.56, $p=0.006$), and moderate and high respectively—but not significant—for both Cretaceous chert (Kendall's tau=0.6 $p=0.23$) and sandstone (Kendall's tau=0.80, $p=0.08$). The high degree of correlation between the final and original estimated volumes may therefore be favoured by extreme values derived from the presence of very small and very big cores.

In summary, the results by raw material show that there are very marked differences both in the estimated volumes of the original selected blanks and in the volumes of the discarded cores. Thus, the smallest blanks correspond to quartz and Cretaceous chert, which, interestingly, are the most intensively reduced. In addition, there are very clear differences in the characteristics and frequencies of the VSEs depending on the raw material.

Diachronic Variability

There is a diachronic trend through the subunit TD6.2, with an incremental presence of Neogene chert cores upwards the subunit, while quartzite decreases. The

Table 1 Weibull parameters (Shape and Scale Values) characterising the reduction intensity distribution of each raw material group

	n	Shape (β)	Scale (α)
Sandstone	5	1.93	55.59
Limestone	3	1.97	60.55
Quartzite	13	1.79	46.58
Quartz	3	3.18	73.68
Cretaceous chert	5	4.84	82.19

proportions of the other raw materials remain stable (Table 2). However, this trend is not statistically significant ($X^2 = 5.45$, $df = 10$, $p = 0.85$).

Regarding the Volumetric Structures of Exploitation, VSE F and VSE A are evenly represented in the three layers (15–20% and 26–33%, respectively), although VSE A does drop to 15% in layer TD6.2.0.1. In contrast, VSE I is not present in layer TD6.2.4 but represents 40% of the cores in TD6.2.2.3 and 20% in TD6.2.0.1; and VSE D plays a relatively important role in TD6.2.4 (25%), while being absent in TD6.2.2.3, and gaining prominence again (9.5%) in TD6.2.0.1. However, the chi-square results ($X^2 = 16.72$, $df = 14$, $p = 0.27$) show that these differences in the frequencies of VSEs are not statistically significant.

The comparison of the Scar Pattern Index (SPI) between the three layers also shows no significant differences either in the central values (K-W $p = 0.97$) or the distribution of the values (K-S $p > 0.05$) (Supplementary Table S11). The three layers present a bimodal SPI distribution (Fig. 9), with values close to 1 being more frequent, indicating that removals tend to be quite parallel to one another (such as in VSE A cores). The second mode, from 0.2 to 0.6, is typical of centripetal, orthogonal, and multipolar organisations (VSEs D, F, and I) (see Supplementary Figure S1). Nevertheless, these cores also generally present SPI values close to 1, indicating a longitudinal unipolar tendency on each of the exploited surfaces.

Table 3 summarises the descriptive statistics for the percentage of extracted volume for the entirety of subunit TD6.2, for each of the layers individually, and the Weibull parameters defining the reduction intensity distribution. Despite the existence of slight differences (Fig. 10), the Kruskal–Wallis and Kolmogorov–Smirnov tests show that these are not statistically significant, neither in the central tendency (K-W $p = 0.34$) nor the distribution (K-S $p > 0.05$) (Supplementary Table S12). This inter-layer homogeneity is also seen in the estimated volumes of the original blanks (Table 4), where no statistically significant differences were found (K-W $p = 0.32$), (K-S $p > 0.05$) (Supplementary Table S13).

Weibull distributions indicate similar discard patterns for the three layers, with very similar β and α values, especially in the case of TD6.2.0.1 and TD6.2.4, where there is a markedly attritional discard pattern, which means that the discard ratio increases as reduction advances. In TD6.2.2.3, the survival curve is slightly lower, although the increase in the discard ratio as reduction advances is maintained (Fig. 11).

In summary, the three layers show similarities in (1) the raw materials used, (2) the estimated volumes of cores, (3) the types and frequencies of VSEs, (4) the core

Table 2 Frequencies of cores according to layer and raw material. No identifiable cores were included

	<i>Sandstone</i>	<i>Limestone</i>	<i>Quartzite</i>	<i>Quartz</i>	<i>Cretaceous chert</i>	<i>Neogene chert</i>	<i>Total</i>
<i>TD6.2.0–1</i>	2 (9.52%)	2 (9.52%)	3 (14.29%)	2 (9.52%)	4 (19.05%)	8 (38.10%)	21 (100%)
<i>TD6.2.2/3</i>	1 (5.88%)	1 (5.88%)	5 (29.41%)	1 (5.88%)	2 (11.76%)	7 (41.18%)	17 (100%)
<i>TD6.2.4</i>	2 (16.67%)	1 (8.33%)	5 (41.67%)	1 (8.33%)	2 (16.67%)	1 (8.33%)	12 (100%)
<i>TD6.2</i>	5 (10%)	4 (8%)	13 (26%)	4 (8%)	8 (16%)	16 (32%)	50 (100%)

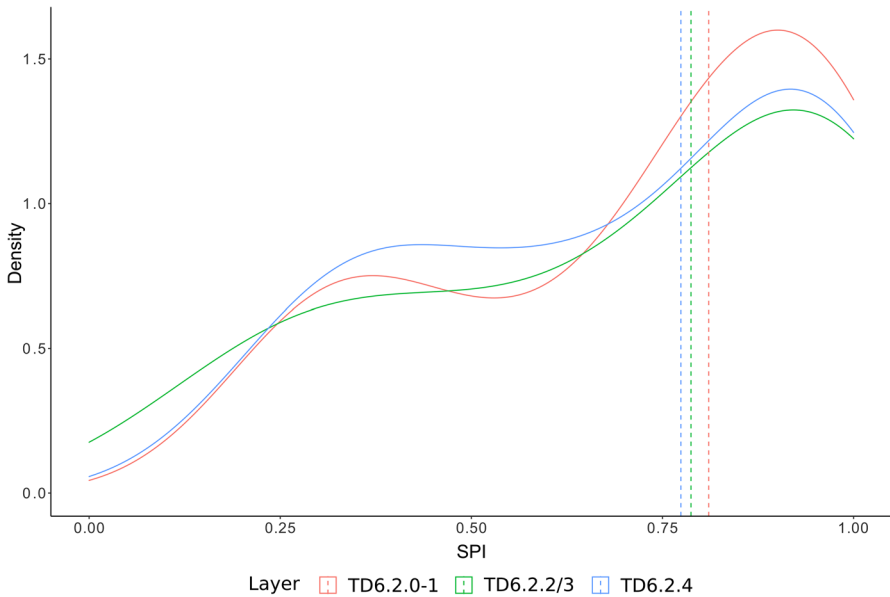


Fig. 9 Density plot showing SPI values according to different layers. Dotted points mark the median of each layer

scar patterns (SPI), and (5) the Weibull distributions of reduction intensities. This may imply that the patterns of lithic management in the three layers remain stable throughout the entire reduction sequences, from the moment of blank selection, the knapping strategies applied, and the reduction intensity at the time of discard.

Discussion

The VRM-based study of the case-by-case core reduction intensity from the TD6.2 *Homo antecessor* occupations highlights markedly different raw material management patterns, from the selection of blanks to the discarding stage.

The estimated volumes of the original blanks show that small and homogeneous Cretaceous chert and quartz blanks were selected. This pattern, however, is not

Table 3 Descriptive statistics of the percentage of extracted volume (PEV) according to layer

	<i>n</i>	Mean	Median	SD	CV	Shape (β)	Scale (α)
TD6.2.0.1	13	51.16	50.14	21.06	41.17	2.55	61.61
TD6.2.2.3	7	37.41	40.31	26.03	69.56	1.51	50.35
TD6.2.4	9	41.44	36.13	17.62	42.52	2.12	53.5
TD6.2	29	44.83	42.54	21.45	47.85	2.15	52.73

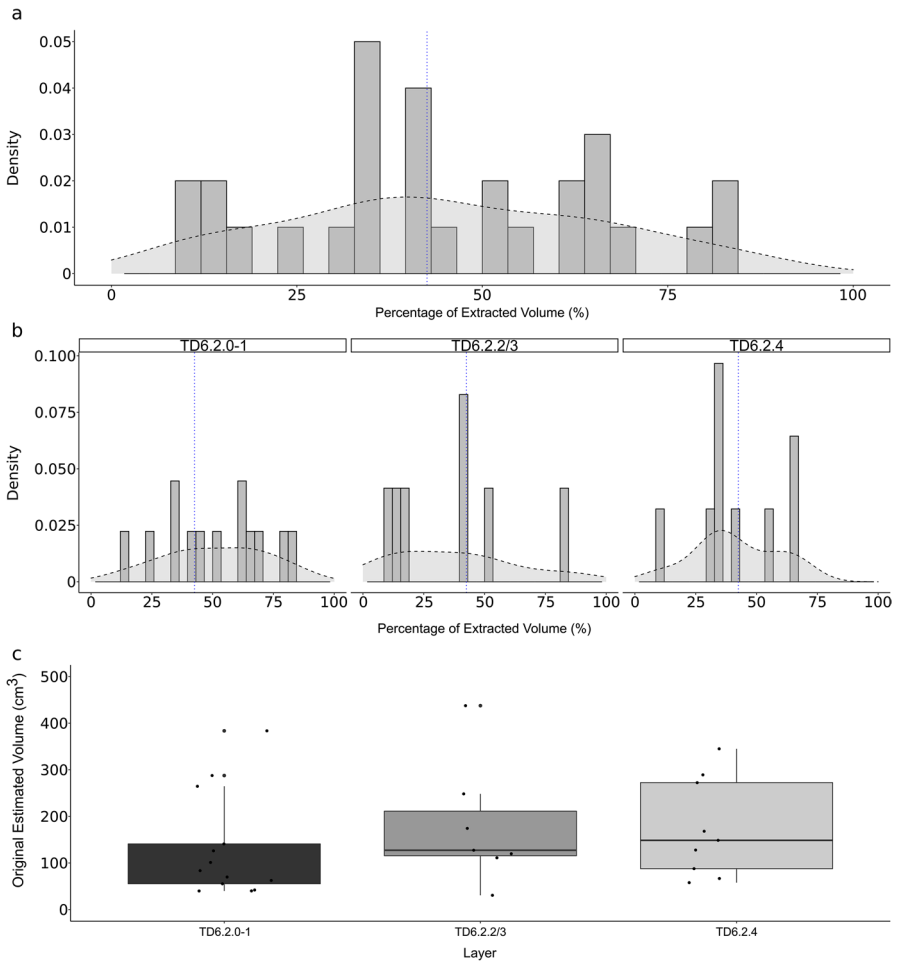


Fig. 10 **a** Histogram with the percentage of estimated extracted volume of TD6.2. **b** Histogram with the percentage of estimated extracted volume according to layer. **c** Boxplot with estimated original volumes according to layer. For figures **(b)** and **(c)**, the blue dotted line indicates the median

Table 4 Descriptive statistics of the estimated original volume (OEV) according to layer

	<i>n</i>	<i>Mean</i>	<i>Median</i>	<i>SD</i>	<i>CV</i>
<i>TD6.2.0.1</i>	13	130.56	83.55	111.10	85.09
<i>TD6.2.2.3</i>	7	178.46	127.31	131.97	73.95
<i>TD6.2.4</i>	9	173.72	148.61	104.56	60.19
<i>TD6.2</i>	29	155.52	126.13	112.57	72.38

behaviourally driven but rather determined by the available blank sizes within the procurement area (Carbonell *et al.*, 1999; Terradillos-Bernal & Rodríguez-Álvarez, 2014). Considering that the most homogeneous Cretaceous chert variety has a small

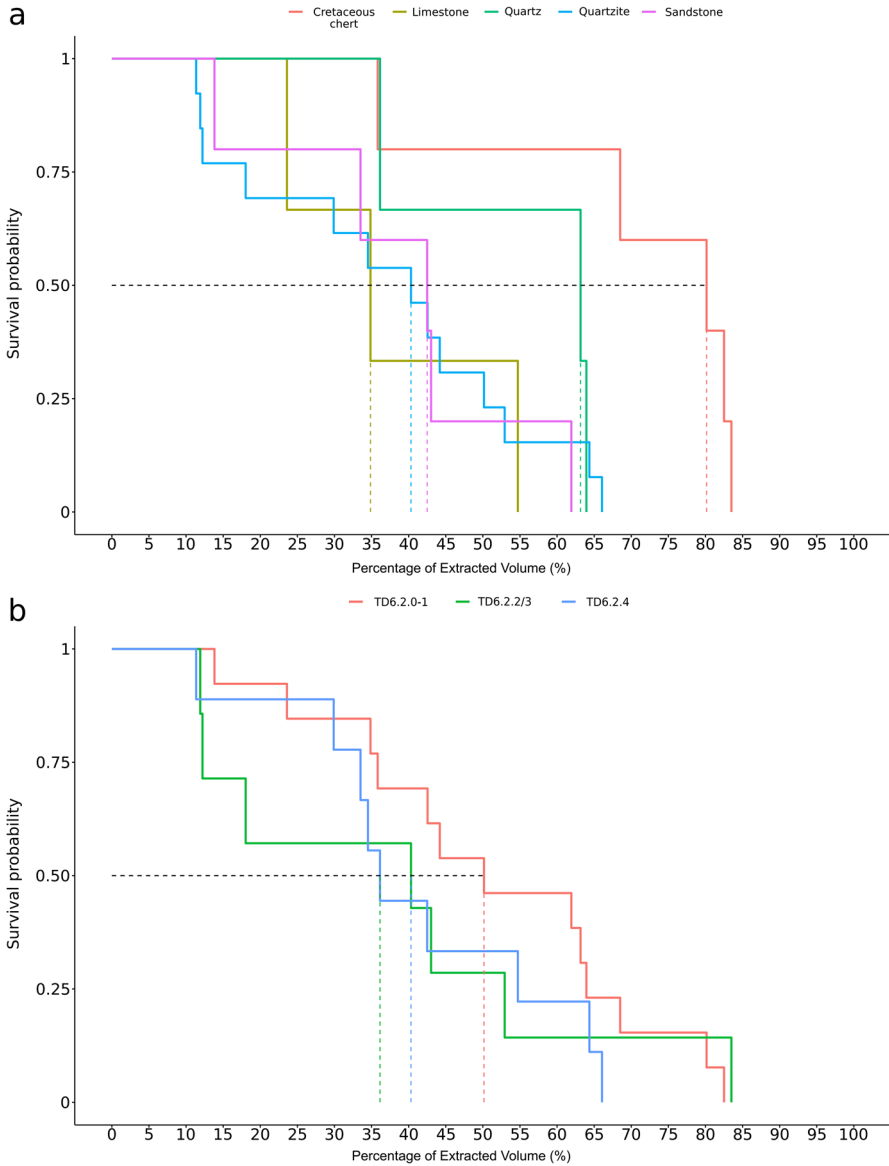


Fig. 11 Kaplan–Meier survival probability plot. **a** According to raw materials. **b** By layers

size (Valdecuende formation), the estimates of the original blank size may suggest that quality might have been far more important than size.

Quartzite and sandstone display greater variability in size and shape, signalling a less patterned size selection. The selected blanks were large angular, tabular, and thick cobbles pointing to flexible shape selection. Previous works (Ollé *et al.*, 2013; Terradillos-Bernal & Rodríguez-Álvarez, 2014) have also suggested that there is

little selection of fluvial materials in terms of quality, as the assemblage contains a large proportion of coarse-grained rocks.

This pattern is similar for the Neogene chert. Even though the original sizes of the blanks cannot be estimated through VRM, the final volume of the cores shows a great range of variability, that together with the morphological diversity of the nodules, points to shape and size having scarce influence on the selection.

This interpretation is reinforced by the lack of correlation between the estimated original volumes of the blanks and the reduction intensity, showing that there was no tendency to further reduce the larger blanks, nor vice versa. Original size was not, then, a limiting factor when it came to reduction intensity, even though this seems to have determined the reduction strategies applied.

Four different paths relating production strategies and discard pattern have been identified through the analysis of the reduction intensity patterns: (i) the early discarding of the core after a short series of removals; (ii) the maintenance of a unipolar longitudinal exploitation scheme (VSE A); (iii) the rotation of the core by changing the percussion surface while maintaining the same flaking surface, generating bipolar unifacial orthogonal exploitation systems (VSE C); or (iv) the rotation of the core by changing both the percussion and flaking surfaces, therefore generating bipolar bifacial orthogonal or opposite exploitation strategies (VSE F) (Fig. 12).

In VSE A, narrow faces were preferentially selected as flaking surfaces, while wide, flat, and mostly cortical surfaces served as percussion platforms (Fig. 3a–c). In this structure, the exploitation could be developed on a restricted front (Fig. 3d) but could also show a greater perimetral development as reduction advanced

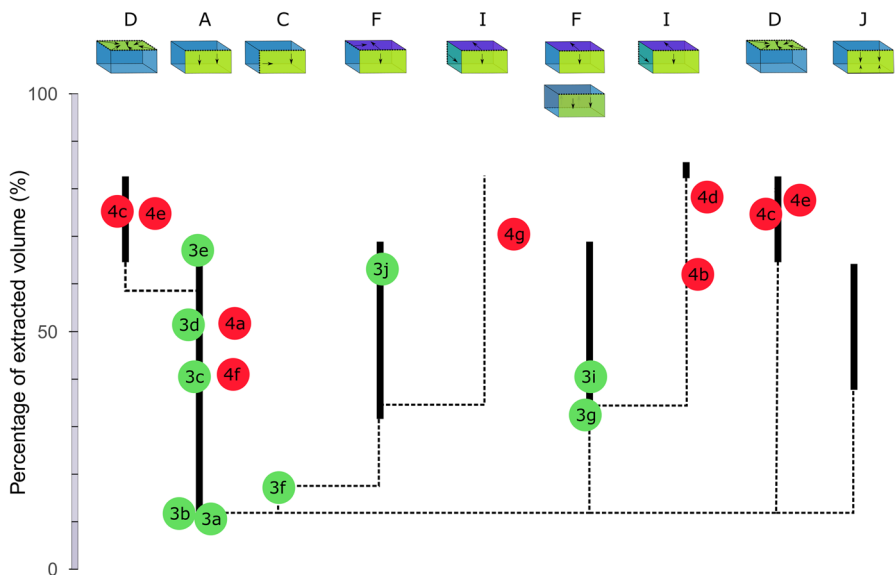


Fig. 12 Interpretation of *Champ opératoire* of the cores from TD6.2. The black lines indicate the range of percentage of volume removed for each VSE. The dotted lines indicate changes between VSE. The green points indicate the estimated percentage of removed volume for the cores in Fig. 3. The red points are the cores of Fig. 4 without VRM application (Neogene chert cores and cores on flakes)

(Figs. 3e and 4a). Depending on the raw material size and flaking orientation, this perimetral development may lead to the centripetal convergence of the scars, generating centripetal trends (VSE D) (Fig. 4c, e), in some cases blurring the boundaries between the two reduction strategies. In VSE C, the cores were rotated by changing the percussion platform (Fig. 3f) and/or the flaking surface (Figs. 3g, j, i and 4b), shaping orthogonal bifacial or multipolar exploitation strategies (VSE F).

From this point on in the reduction continuum, the same exploitation structure could have been maintained until abandonment, or additional changes introduced to the percussion and flaking surfaces, generating multipolar multifacial-type strategies (VSE I) (Fig. 4d, g). The core sizes and remaining volumes indicate that this was not a technical behaviour aimed at maximising core exploitation, and in the case of Neogene chert, we find multifacial multipolar strategies in early and intermediate reduction stages.

The low degree of standardisation in the final core morphologies suggests that raw material constraints played an important role during the reduction process. For that reason, VSE A, F and I may not reflect the application of different strategies or knapping methods *sensu stricto*, which would respond to a predefined volumetric conception. Instead, they seem to be the consequence of a much more limited technical behaviour, where the core variability resulted from a combination of (1) the blank's morphological constraints; (2) the original size; and (3) the more or less systematic application of independent longitudinal unipolar series on different flaking surfaces, while looking for abrupt angles between the percussion and exploitation faces. In addition, the control of the core's morpho-volumetric conditions does not seem to be well-developed, or at least apparently intentional, but it seems that the circumstances of the exploitation, and not the reduction intensity, are those determining when a change of structure occurs.

Quartz and Cretaceous chert display the highest percentage of extracted volume in relation to the original estimated volume, and the longest survival rates, indicating that size affected the rate of reduction advance. In these smaller blanks, the same volume percentage is represented by less volume than in the larger blanks, so that each flake removed from a smaller core equals a greater percentage of extracted volume, meaning greater reduction values were reached more quickly. However, beyond size constraints, the increased reduction observed in quartz and Cretaceous chert seems to be the result of different reasons.

Although it should be noted that the small sample size of some raw material groups means that the reconstructed survivorship curves have quite a large degree of uncertainty, some assemblage-level proxies support the results obtained. The use of flakes as cores and the retouched tool-to-flake ratio (higher in Cretaceous chert, quartzite, and Neogene chert, compared with sandstone, limestone, and quartz), points to a preferential use of the homogeneously textured Cretaceous chert for obtaining small flake tools (Mosquera *et al.*, 2018; Terradillos-Bernal & Rodríguez-Álvarez, 2014). This trend is broadly identified when exploring each layer individually.

Quartz is mostly reduced through the bipolar-on-anvil technique. Cretaceous chert also presents differential reduction strategies, since almost all the centripetal cores are made from this raw material. Probably both the size and quality allowed

the production of overshot flakes covering the entire thickness of the cores, advancing the reduction through adjacent removals that may have ended up shaping centripetal multipolar types (Mosquera *et al.*, 2018). However, experimental work on Cretaceous chert shows how medium-to-high striking force is necessary in advanced reduction phases to overcome important difficulties, such as the small size and thick shapes of the nodules, as well as the occasional presence of internal irregularities and fissures (Terradillos-Bernal & Rodríguez-Álvarez, 2014, 2017). This could explain why, in some cases, bifacial orthogonal or multipolar multifacial strategies were developed.

The VRM shows that quartzite and sandstone were not intensively reduced through the TD6.2 occupations. This is consistent with the abundance of cortical surfaces, since almost all the sandstone and quartzite cores retain at least 50% of their cortex. Low reduction levels, together with non-selective procurement in terms of size and quality, could be related to a more expedient behaviour where the particular reduction strategies identified may have depended on the size and shape of the material available, and on the types of sharpened-edges wanted (Nelson, 1991).

Also, the variability in reduction intensity suggests that the hominins from TD6.2 transported the blanks to the cave and developed systematic in situ knapping. This interpretation is reinforced by the presence of refits, by the abundance of flat, single-faceted, or natural platforms within the flake assemblage (see Mosquera *et al.*, 2018), and also by very large cores there abandoned. The presence of these large discarded cores may be related to either (i) the planned storage of material for later use and/or (ii) some unknown reason driven by the possibility of easy replacement, which would indicate a profound knowledge of the environment and resource distribution and availability (Terradillos-Bernal & Rodríguez-Álvarez, 2014).

The discarding patterns observed through the Weibull distributions do not show any significant inter-layer differences, suggesting that there were no major changes in the economic management of lithic resources. This, along with the similarities reported for the rest of the lithic assemblage (Mosquera *et al.*, 2018), could reflect the same occupation dynamics during the formation of TD6.2. However, when making inferences about the occupation patterns through reduction data, it should be noted that TD6.2 has only been partially excavated. Furthermore, the resolution of the reduction distribution curves depends directly on the resolution of the assemblage (Morales, 2016). This resolution is directly dependent on factors such as the time of formation of the assemblages and depositional and postdepositional processes as well as sampling size. In spite of being characterised as a residential site (Carbonell *et al.*, 1999; Díez *et al.*, 1999; Mosquera *et al.*, 2018; Saladié *et al.*, 2011, 2014, 2021), TD6.2 is a time-averaged unit resulting from the overlap of many occupational events with different characteristics (Canals *et al.*, 2003; Vallverdú *et al.*, 2001) and therefore may reflect a cumulative combination of different strategies and/or occupation dynamics that in many cases cannot be isolated from one another (Saladié *et al.*, 2011, 2014).

Despite this, there are some elements that point to a markedly expedient behaviour, understood as a response characterised by the minimisation of technological effort in circumstances where time, resources, and place of use are highly predictable (Bamforth, 1986; Nelson, 1991; Parry & Kelly, 1987). The abundance,

variability, and proximity of lithic resources (García-Antón, 2016; Terradillos-Bernal & Rodríguez-Álvarez, 2014, 2017), together with a good knowledge of the environment, could explain the low degree of reduction and volumetric exhaustion of the cores. Other elements also considered indicative of expedient behaviours (Nelson, 1991), such as the systematic transport of cores to the cave to be knapped in situ, together with the presence of large nodules as a possible result of planned stockpiling, point to a regular reuse of the cave, which reinforces the hypotheses of TD6.2 as a referential site.

This seems to be in line with the knapping strategies represented, in which there is no “curated” behaviour, since it is not possible to observe the maintenance of the volumetric conditions of the cores. Instead, these hominins reflect a more situational behaviour, constantly adapting to the circumstances of the exploitation.

This expedient technological behaviour does not necessarily imply that these hominins are mere passive subjects completely predetermined by environmental conditions. Obviously, environmental circumstances condition technological strategies to some extent, but there are certain behavioural patterns that point to a more “active” adaptive behaviour.

In general, there is a clear three-fold reduction sequence pattern according to the raw materials: (i) quality-driven selection of Cretaceous chert, contrasting with the size- and shape-independent selection of other lower-quality raw materials such as quartzite, sandstone, or even Neogene chert; (ii) the presence of different strategies and knapping techniques adapted to the raw material characteristics and the particular knapping evolution (see Fig. 11); and (iii) a more intense reduction of Cretaceous chert and quartz, contrasting with the less-reduced sandstone and quartzite. This, together with other assemblage proxies, reinforces the hypothesis of a differential raw material management where TD6.2 hominins adapted their knapping strategies through the reduction continuum and reduced cores differently, according to the particular constraints of each raw material.

Although these hominins were not able to substantially modify the volumetric conditions of the original blanks to develop specific or systematic reduction strategies, they were able to develop long reduction sequences through the application of relatively simple knapping strategies on raw materials with very different characteristics and formats. This would indicate a great control of the elementary knapping gestures (Cueva-Temprana *et al.*, 2019; Geribàs *et al.*, 2010), as suggested by some previous actualistic studies in both humans (Roux & David, 2005) and chimpanzees (Bril *et al.*, 2012, 2015). This mastery of the elementary gestures would explain the lack of sorting of the blanks in morphological terms, since it would not be necessary to select blanks with specific volumetric conditions.

In this sense, the situational character of the knapping strategies, which may represent rather simple cognitive mechanisms (Moore & Perston, 2016), reflects a flexible behaviour that requires a certain degree of problem-solving abilities and perceptual ability (*i.e.*, subtargets are adjusted during knapping through turning and rotating gestures). This behaviour ultimately requires a perceptual-motor skill for effectively detaching flakes (Roux & David, 2005).

Furthermore, it is necessary to consider that technological behaviour is only one aspect of human behaviour, and in this sense, TD6.2 hominins were able to develop

complex behavioural dynamics, such as hunting and the selective transport of carcasses of large ungulates, all of which could involve the sharing of biotic resources and social cooperation (Saladié *et al.*, 2011, 2014).

This demonstrates their polyhedral behavioural character, in which multiple aspects are developed, although not all of them in a homogeneous way or with a simultaneous appearance. Some aspects documented in TD6.2 require a certain cognitive and behavioural complexity, such as the anticipatory behaviour observed in the selection of lithologies according to their workability and intended use, and in the differential transport of ungulate carcasses to minimise the chances of competition with other predators (Saladié *et al.*, 2011, 2014). Meanwhile, other aspects would be addressed with simpler and more expedient solutions, but not less efficient for their purpose, such as technological organisation and tool production techniques, whose (scattered) presence in virtually the entire European subcontinent would show the adaptive success of this kind of technological behaviour to different ecological contexts.

In that way, the European Early Pleistocene context shows a certain degree of continuity in the adaptation of knapping strategies to raw material constraints, where differences may correlate to local particularities. In this sense, the association of knapping techniques or methods with raw materials and/or sizes and/or shapes is a common feature of the European Early Pleistocene. For example, the bipolar-on-anvil technique for quartz exploitation has been documented at sites such as Pont-de-Lavaud (France), applied to small- and medium-sized polyhedral and ovoid quartz cobbles (de Lombera-Hermida *et al.*, 2016); and Vallparadís, used on small angular quartz fragments (García *et al.*, 2013). Bipolar-on-anvil exploitation has also been found at Fuente Nueva 3 and Barranco León, but exclusively associated with small flint blanks (Barsky *et al.*, 2015), while at Ca` Belvedere di Monte Poggiolo it was mainly applied during the first phases of the reduction sequence to create percussion platforms (Arzarello & Peretto, 2010). Although bipolar-on-anvil reduction seems to have played a different role at each of these sites (de Lombera-Hermida *et al.*, 2016), in TD6.2 it appears to have been a technical response to the technical constraints of quartz.

The pattern of differential selection is not exclusively restricted to the bipolar-on-anvil technique. At Dmanisi it seems that raw materials were exploited with different intensities depending on the quality, where two groups were identified: a first set displaying mainly unipolar strategies is quality-independent, where the morphology of the blank is the most important aspect; and a second group which was quality-dependent and shows complex multipolar series (Baena *et al.*, 2010). At Pirro Nord and Ca` Belvedere di Monte Poggiolo, knapping methods were strictly related to the raw material dimensions. The small blanks were exploited using centripetal methods while unidirectional and multidirectional strategies were applied to the bigger ones (Arzarello & Peretto, 2010; Carpentieri & Arzarello, 2021). At Barranco León and Fuente Nueva 3 the bidirectional or centripetal strategies were applied on flat tabular flint blocks, while orthogonal/multiplatform methods were used for thicker blocks (Barsky *et al.*, 2010; Toro-Moyano *et al.*, 2011). At Pont-de-Lavaud, large elongated blanks were chosen for unipolar longitudinal, centripetal, and orthogonal knapping methods (de Lombera-Hermida *et al.*, 2016). At other sites, cores are

scarce or absent, such as at Bois-de-Riquet (Bourguignon *et al.*, 2016), Pakefield (Parfitt *et al.*, 2005), Atapuerca-TE9 (de Lombera-Hermida *et al.*, 2015), Atapuerca-TD3-4 (Ollé *et al.*, 2013), and Happisburgh 3 (Parfitt *et al.*, 2010), therefore making it impossible to identify patterns of blank selection and knapping strategies.

Conclusions

The combination of technological and quantitative analyses of reduction intensity in cores allows a more precise reconstruction of technological behaviour and a more in-depth study of the adaptive strategies of Early Pleistocene European hominins.

The technological behaviour inferred through our study shows a lack of standardisation both in the morphological selection of blanks and in the knapping sequences, which reflect a great flexibility and adaptability to the original format of the raw materials. In this sense, the development of the knapping sequences shows immediate management and the ability to solve problems as they come up rather than the advance planning required by methods with greater predetermination (*i.e.* mental planning when organising and sequencing the different subsequent actions).

However, in order to successfully adapt to the characteristics of the raw materials, it is necessary to know, either explicitly or implicitly, the limitations and possibilities offered by each lithology. In TD6.2 we can see diverse exploitation of different lithologies, and differential raw material management in terms of reduction intensity, with the best-quality materials being the most reduced ones. Together with complementary strategies for lower-quality materials, this demonstrates that these hominins possessed good knowledge of raw material properties and implemented a certain degree of planning, to the extent that raw materials were selected for their intended use. Therefore, we can confirm that despite not applying a wide variety of knapping techniques or carrying out clearly predetermined schemes, they were not simple opportunistic stone gatherers (Harmand, 2009).

This work, together with previous studies (Carbonell *et al.*, 1999; Mosquera *et al.*, 2018) point to a series of divergences and/or particularities of TD6.2 with respect to the technological context of the European Late Early Pleistocene, such as (1) the production and use of large flakes (> 10 cm) for their subsequent exploitation, (2) the differential reduction of the best quality raw material in comparison with other lithologies and (3) the high percentage of small retouched tools, especially of Cretaceous chert.

Some of these divergences may be a by-product of the available raw materials, such in the case of the production and use of large Neogene chert flakes. Other differences could be explained by methodological aspects. In this sense, this work is the first approach aimed at quantifying the degree of core reduction in the context of European Mode 1.

In our opinion, the most significant differential element is the high percentage of retouched tools, and the preferential selection of Cretaceous flint to produce them. This aspect has been interpreted as a more evolved behaviour, which would represent a later stage in the diversification (*sensu* Carbonell *et al.*, 2016) of archaic technology (Mosquera *et al.*, 2018). It could also be a consequence of the occupation

intensity and recurrence in TD6.2 as a referential site, while other assemblages would represent more sporadic occupations and therefore may have a different expression in the lithic assemblage's structure.

In any case, despite the behavioural divergences observed with other European Mode 1 assemblages, the adaptation of the knapping strategies to the raw material constraints is a common feature to all of them, and the recorded variability can be explained in terms of the qualities and characteristics of the lithologies available in each context and the time of discard.

Unfortunately, the lack of reduction intensity studies for the European Early Pleistocene results in the absence of a comparative framework for the discarding patterns at different types of sites and their interrelation with the knapping dynamics or according to occupational dynamics. This would allow us to further interpret the role these variables played in the technological variability of early human occupations in Europe and construct more precise inferences about their techno-economic behavioural adaptations to different environmental or lithological contexts and their evolution.

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Declarations

Competing Interests The authors declare no competing interests.

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Authors and Affiliations

Diego Lombao^{1,2}  · **José Ramón Rabuñal**^{3,4} · **Juan Ignacio Morales**^{1,2} · **Andreu Ollé**^{1,2} · **Eudald Carbonell**^{1,2} · **Marina Mosquera**^{1,2}

✉ **Diego Lombao**
dlombao@iphes.cat

✉ **Juan Ignacio Morales**
jmorales@iphes.cat

¹ Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA), Zona Educacional 4, Campus Sescelades URV (Edifici W3), 43007 Tarragona, Spain

² Departament d'Història i Història de l'Art, Universitat Rovira I Virgili, Avinguda de Catalunya 35, 43002 Tarragona, Spain

³ Instituto Universitario de Investigación en Arqueología Y Patrimonio Histórico (INAPH), Universidad de Alicante, Carretera de San Vicente del Raspeig s/n, San Vicente del Raspeig, 03690 Alicante, Spain

⁴ Department of Archaeology and Heritage Studies, Aarhus University Moesgård, Moesgård Allé 20, 8270 Højbjerg, Denmark