JOURNAL OF QUATERNARY SCIENCE (2023) 38(5) 658–684 ISSN 0267-8179. DOI: 10.1002/jqs.3501

Journal of Quaternary Science

Low-cost technologies in a rich ecological context: Hotel California open-air site at Sierra de Atapuerca, Burgos, Spain

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Received 3 May 2022; Revised 25 November 2022; Accepted 23 December 2022

ABSTRACT: Hotel California is part of a network of open-air Neanderthal sites located in the Sierra de Atapuerca (Burgos, Spain). In this study, we examine the technology of the lithic assemblages recovered from this site's archaeological levels 3 to 7, which are characterised by the use of local raw materials, non-hierarchical centripetal exploitation systems, systematic production of flakes and few retouched items. This type of expedient technology is repeated throughout the entire sequence, which spans Marine Isotope Stages (MIS) 3 to 4. Through a comparison with the technocomplexes and occupation histories of surrounding sites – including a re-evaluation of the published chronology for the nearby site of Fuente Mudarra, which is now dated exclusively to MIS 5 – we examine whether the detected pattern is applicable to the rest of the Atapuerca Mousterian record and if this expedient behaviour has equivalents in other sites in the region. Our findings show that the lithic procurement, exploitation and configuration strategies employed at the Sierra de Atapuerca open-air sites were constant over broad time periods spanning MIS 5 to 3, in contrast to the technological sequences observed at other nearby sites on the Northern Iberian Plateau. The recurrent settlement of these open-air Neanderthal sites over tens of thousands of years and the consistent use of expedient technologies during different occupation periods is likely attributable to the rich ecological context of the Sierra de Atapuerca environs.

KEYWORDS: expedient technology; lithic technology; Neanderthals; open-air sites; Sierra de Atapuerca

Introduction

The Sierra de Atapuerca occupies a strategic enclave within the Iberian Peninsula, in a natural corridor that connects the basins of the rivers Ebro and Duero. This privileged space contains one of the most important archaeological complexes in Europe, and more than 40 years of archaeological work has uncovered records of the last million years of European prehistory. These have allowed us to learn about the occupation of different hominids and their behaviour, from subsistence strategies to the cultural and technological aspects of their lives.

The long periods of occupation that are documented in the Sierra de Atapuerca have made it possible to study the technological evolution of the different hominids who inhabited it, from the first technologies of Mode 1, found in level TE9 of the Sima del Elefante and the lower levels of the Gran Dolina; through to Mode 2 assemblages in Galería and TD10; and culminating with the transition from Mode 2 to Mode 3, which is observed in TD10.1 (Ollé *et al.* 2013; de Lombera-Hermida *et al.* 2020).

There are several sites with evidence of a Neanderthal presence across the Sierra de Atapuerca, both in caves and open landscapes, which have, since the year 2000, provided information on the way of life and settlement patterns of the Neanderthal groups that lived in this region. Following an extensive surface survey, the documentation of 30 Marine Isotope Stage (MIS) 5–3 open-air sites has also allowed us to study aspects of how these groups procured biotic and abiotic resources, infer the activities that were carried out in this space, and learn how these hominids managed and used the area that they inhabited (Navazo, 2006; Navazo *et al.* 2008; Navazo *et al.* 2011; Arnold *et al.* 2013; Ollé *et al.* 2013; Navazo and Carbonell, 2014; Navazo *et al.* 2017; Santamaría *et al.* 2021; Santamaría Cabornero *et al.* 2021).

So far, five Neanderthal sites have been excavated: two cave sites, Cueva Fantasma and Galería de las Estatuas, located in the upper level of Cueva Mayor's karstic complex (Arsuaga *et al.* 2017; Demuro *et al.* 2019a); and three open-air sites (Fig. 1a), Hundidero, located by a pond (Navazo *et al.* 2011), and Fuente Mudarra and Hotel California, on the bank of the Pico River (Arnold *et al.* 2013; Santamaría *et al.* 2021). These, along with surface assemblages, provide an interesting picture of a Neanderthal territory that is framed around different land features.

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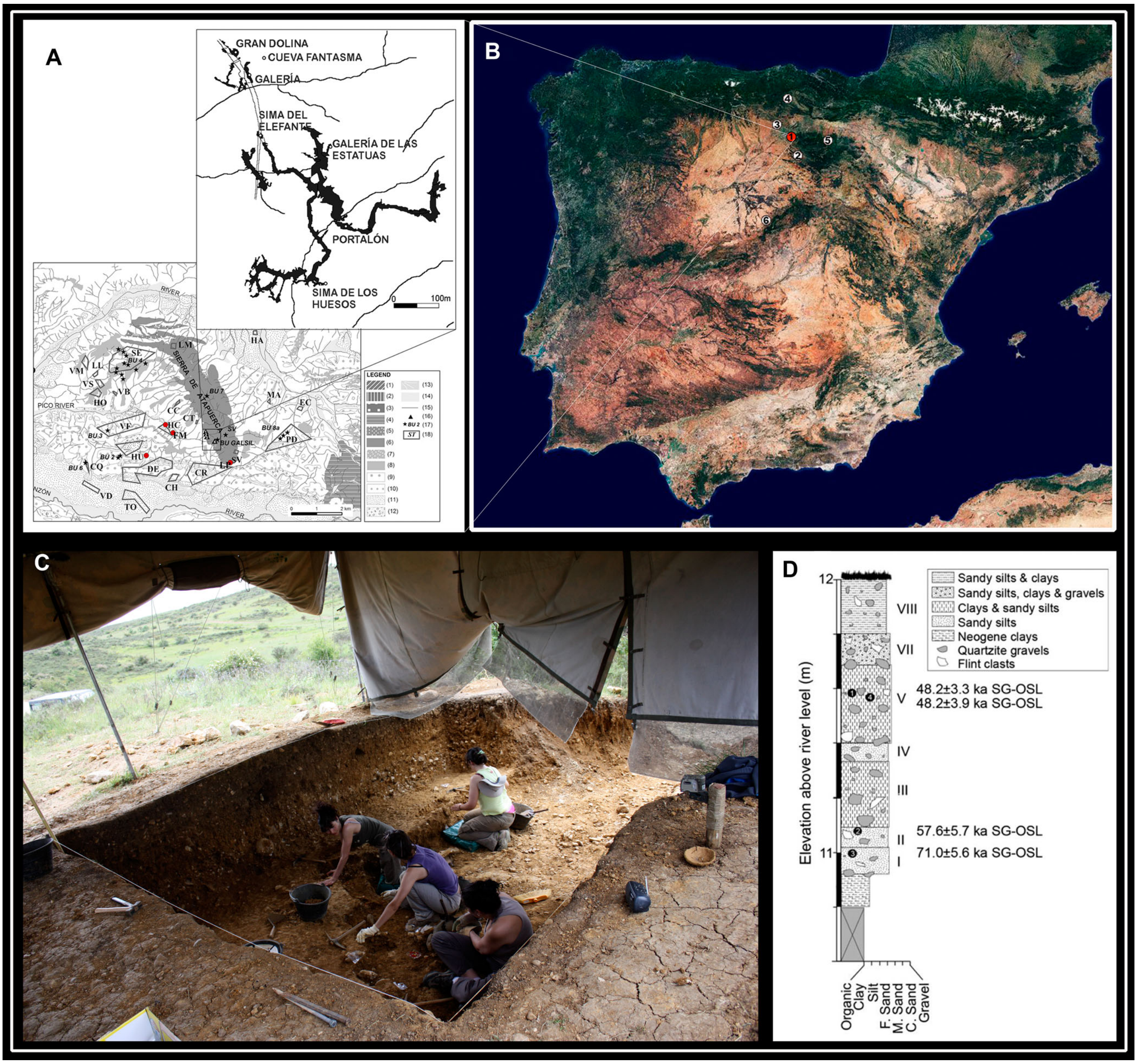

Figure 1. (A) Map of the upper Pleistocene open-air sites. Modified from (Navazo *et al.* 2008). (1): Cambrian (metasandstones and slates); (2): Carboniferous (conglomerates, sandstones and slates); (3): Triassic (conglomerates and sandstones); (4): Lower Cretaceous (limestones and quartzite conglomerates); (5): Lower Cretaceous siliciclastic detritic sediments; (6): Upper Cretaceous (limestones and dolostones); (7): Middle Miocene sediments with quartzite conglomerates; (8): Middle Miocene limestone with nodules of flint; (9): Lower Pleistocene terraces; (10): Middle Pleistocene terraces; (11): Upper Pleistocene terraces; (12): Hundidero alluvial deposits; (13): colluvial deposits; (14): cones; (15): floodplain and bottom valleys; (16): drainage network; (17): Palaeo-archaeological sites located in the Sierra de Atapuerca endokarstic system; (18): sampling in primary flint outcrops; (19): archaeological occurrences. The red dots indicate the locations of the Hundidero, Hotel California, Fuente Mudarra and La Paredeja sites. (B) Location of the sites mentioned in the text within the Iberian Peninsula context. (1): Atapuerca complex, (2): Cueva Millán y La Ermita, (3): Valdegoba, (4): Prado Vargas, (5): Peña Miel and (6): Abrigo del Molino. (C) Hotel California open-air site. (D) Stratigraphic profile and OSL dating of Hotel California. [Color figure can be viewed at wileyonlinelibrary.com]

There is evidence that Neanderthal groups repeatedly settled in the Sierra de Atapuerca over tens of thousands of years, making this landscape one of the best places to learn about different aspects of the daily lives of *Homo neanderthalensis*. In this study, we present a detailed examination of the archaeological remains of Hotel California with the aim of broadening understanding of the settlement model and technological behaviours of the Neanderthal groups in this area. As part of our technological comparisons with surrounding sites, we re-evaluate the published chronology for the nearby site of Fuente Mudarra using the same single-grain optically stimulated luminescence (OSL) dating approach used at Hotel California and Galería de las Estatuas, thereby ensuring more consistent site history interpretations across the area.

Hotel California

The site

Archaeological remains were originally detected from surface surveys undertaken on the left (south) side of the Pico River, where two sites with Mousterian chronologies have since been excavated: Fuente Mudarra (Santamaría *et al.* 2021) and Hotel California, whose archaeological remains are the focus of this paper. Hotel California is an open-air site located in the Sierra de Atapuerca, nearly 2 km from the Railway Trench ('Trinchera del Ferrocarril') sites. This site was examined during the campaigns of 2006–2010, when a total of eight geological units were excavated over a surface of 23 m^2 (Fig. 1c). Five of these eight geological units contain Mousterian lithic technology spanning an age of 71.0 ± 5.6 to 48.2 ± 3.3 thousand years (ka) (Arnold *et al.* 2013; Navazo and Carbonell 2014). The occupations of the different archaeological levels took place within colluvial deposits formed on a gentle slope some 11–12 m above the level of the Pico River (Arnold *et al.* 2013).

Geological context

The 1.0–1.5 m sedimentary sequence of Hotel California (HC) comprises massive sandy silts (Units I, II and III), clays with sandy silts and gravels (Unit VII), and sandy silts (Unit VIII), lying on Neogene marls and shales.

Units I–V represent the main horizons from which Mousterian lithic artefacts were recovered. Although they are not directly affected by anthropogenic action, these units show physical evidence of post-depositional processes such as bioturbation (anthills and roots), illuviation and desiccation cracks. However, it is not very likely that such localised processes caused a significant spatial redistribution of decimetric clasts and lithic artefacts. Subsequent to the occupations, the levels underwent some episodes of waterlogging which can be identified by the manganese stains observed in the sediment and in some pieces. These post-depositional processes produce alterations in some pieces but not in the spatial distribution of the assemblage. Furthermore, the orientations of the pieces are not arranged in such a way that their movements can be noticed. This waterlogging is seen in the dorsal scars rounded by water, but the edges of the pieces remained fresh.

Clasts are angular and subrounded, made of flint and quartzite, which are dispersed through these horizons, particularly in Units III–VIII. The massive structure and the generalised presence of floating clasts indicate that these deposits probably accumulated by gravitational flows (debris and mud flows) eroding the Neogene and Pleistocene (Arlanzón fluvial terraces) material outcropping in the upper valley hillside. The siliciclastic composition of the Hotel California sequence is in marked contrast to the calcareous sediments transported currently by the Pico River, which reveals the breadth of materials that supplied Hotel California. The uppermost 20–30 cm of Unit VIII's sedimentary sequence and assemblages in Unit VII are located within a ploughed area and are poorly conserved as a result of repeated mechanical mixing.

The correspondence between the geological units and archaeological levels addressed in this paper is as follows: Unit VIII corresponds to Level 0; Unit VII corresponds to Levels 1 and 2; Unit V corresponds to Level 3; Unit IV to Level 4; Unit III to Level 5; Unit II to Level 6; and Unit I corresponds to Level 7. Level 0 is an organic stratum; Levels 1 and 2 contain lithic artefacts, but these are post-depositionally mixed because of agricultural activity. The current study analyses archaeological materials from Levels 3–7.

Dating

The chronology of the Hotel California site has been published by Arnold *et al.* (2013). Four single-grain OSL samples were obtained from freshly cleaned exposures at this site underneath thick black sheeting. Two replicate samples (HC10-1 and HC10-4) were obtained from the same depth in the uppermost *in situ* horizon (Unit V) to test for internal consistency of the dating results. The two remaining samples (HC10-2 and HC10-3) were taken from the lowermost sedimentary horizons overlying the Neogene deposits (Units I and II, respectively). This sampling strategy ensured that the resultant OSL ages bracket the entire *in situ* archaeological record (Arnold *et al.* 2013).

The final OSL ages reveal that the sediments associated with the *in situ* Mousterian lithics were deposited over a period of ~23 ka between 71.0 ± 5.6 ka and 48.2 ± 3.3 ka (Fig. 1d). This chronology constrains the Middle Palaeolithic occupation of the Hotel California site to between early MIS 4 (c. 57–71 ka) and the middle of MIS 3 (c. 29–57 ka) at, or prior to, the occurrence of Heinrich Event 4 at c. 45 ka (Arnold *et al.* 2013).

The nearby site of Fuente Mudarra exhibits a deeper stratigraphic sequence, which has been initially dated to between early MIS 5 (123.7 ± 8.8 ka) and at least early MIS 3 (>56.8 ± 3.3 ka) using conventional (multiple-grain aliquot) OSL dating (Santamaría *et al.* 2021). Five OSL samples were collected from sedimentary units FM4a, FM5, FM6, FM7 and FM8 at Fuente Mudarra as part of the initial chronological study. However, it was only possible to calculate finite OSL ages for the lowermost three samples from FM6–FM8, which ranged between 106.7 ± 7.3 ka and 123.7 ± 8.8 ka. In contrast, the upper two samples from FM4a–FM5 yielded non-finite, minimum age estimates of >56.8 ± 3.3 and >87.1 ± 5.2 ka, potentially due to signal saturation complications and multiple-grain averaging effects.

Arnold *et al.* (2012a; 2013) cautioned that the reliability of multiple-grain OSL dating at the neighbouring Hotel California site is compromised by the presence of significant populations of aberrant grains with high sensitivity-corrected natural signals (particularly grains with non-intersecting and saturated natural signals). Such biasing averaging effects could potentially compromise some, or all, of the existing multiple-grain OSL ages at Fuente Mudarra, as suggested by the non-finite results reported by Santamaría *et al.* (2021). Consequently, the chronology of the five OSL samples from Fuente Mudarra is re-evaluated in the current study using the same single-grain OSL dating approach employed previously at Hotel California.

Methodology

Lithic analysis of Hotel California

A total of 1982 cultural items were recovered during Hotel California's five excavation campaigns, of which 1445 lithic artefacts belonging to the site's Levels 3–7 have been studied.

Hotel California's lithic industry has been analysed using the criteria established in the Logical Analytical System (Carbonell, Guilbaud and Mora 1983; Carbonell and Mora, 1986; Carbonell *et al.* 1992; 1995; 1999; 2001; Carbonell and Rodríguez 2002) (Tables 1–2). Other authors' technological criteria (Vaquero and Carbonell 2003; Carmignani *et al.* 2017; Menéndez 2009; Vaquero 1999) have been incorporated to complement the analysis (Table 1).

Among the criteria used to analyse the cores, we incorporated those proposed by M. Vaquero, including observing aspects like degrees of symmetry and hierarchy, for which we defined the degree of control between the reduction of the cores' volumes and the variability within the centripetal systems of exploitation (Vaquero 1999; Vaquero and Carbonell 2003). We also incorporated L. Carmignani's technical parameters to analyse each core's volumetric concept, platform organisation, direction of removals, and the angle between the debitage surface and the striking platform (Carmignani *et al.* 2017).

We broadened the analysis of positive bases by trying to identify the products derived from centripetal exploitations, and thus differentiating the products of exploitations of parallel and secant planes (Carmignani *et al.* 2017). To do this, one

Table 1. Categories of the logical analytical system (LAS). Adapted from (Ollé *et al.* 2013, Santamaría *et al.* 2021)

Logical analytical system (LAS)	Common terms	LAS subdivision categories	Variables under study
Natural base (nB)	Pebbles, cobbles, hammers or selected blocks	nBa: selected and transported bases nBb: hammerstones with percussion marks nBc: cobble fragments with or without percussion marks	Size, shape, weight and percussion marks
Exploitation First generation negative base of exploitation (1GNBe) Second generation negative base of exploitation (2GNBe)	Cores, cores on flakes	1GNBe: the exploitation of a pebble or block to obtain positive bases 2GNBe: the positive base exploitation to obtain more positive bases (core on flake)	Volumetric concept, striking platform organisation, exploitation methods, symmetry and hierarchy degree, surfaces' preparation degree. (Carbonell *et al.*, 1999; Carmignani *et al.*, 2017; Vaquero, 1999; Vaquero and Carbonell, 2003; Menéndez, 2009)
Positive base (PB)	Flakes and debris	The PB are the products of exploitation (flakes)	PB morphology. Direction of dorsal previous removals, angles between surfaces. (Carbonell *et al.*, 1999) (Carmignani *et al.*, 2017)
Fragmented positive bases (FPB)	Broken flakes	Broken flakes; flakes with preserved point of percussion but incomplete margins	
Fragments of positive base (Frag of PB)	Flake fragments; flakes with absent butt		
Configuration First generation negative base of configuration (1GNBc) Second generation negative base of configuration (2GNBc)	Tools on pebble, tools on flakes	1GNBc: tools on pebble, cobble, or block 2GNBc: tools on flakes	(Carbonell *et al.*, 1999) Faciality, centripetal character, retouching angle, depth, mode, delineation, type. (Laplace 1972) Typology
Fragments (FRAG)	Angular fragments		
Indeterminate (INDET)	Unidentifiable lithic items		

must consider angles of scars on the dorsal surface, the angle between the butt and the ventral face, and the direction of previous scars. Exploitations with secant planes give rise to centripetal (A1) and chordal (A2) products, while the products of exploitations with parallel planes characterise centripetal (B1) and chordal (B2) categories (Carmignani *et al.* 2017).

For the typometric analyses, we have followed Bagolini (1968). For the second-generation negative bases of configuration (2GNBc), we have used the Logical Analytical System variables (see Table 1) (Carbonell *et al.* 1999; Rodríguez, 2004). We also identified them using Laplace's Analytical Typology (1972). All of the gathered data were processed with the SPSS Statistics v25 statistical program.

Single-grain OSL dating of Fuente Mudarra

The revised OSL dating study of Fuente Mudarra focusses on single-grain analyses in order to gain maximum insights into any potential methodological complications that could affect dating reliability in this setting, including the presence of insufficiently bleached grain populations (e.g. Arnold *et al.*, 2008, 2009) and aberrant grains displaying unsuitable luminescence properties (Demuro *et al.*, 2008, 2013; Arnold *et al.*, 2012a). The single-grain OSL dating study was conducted on the same five sediment samples originally used in the multigrain OSL dating study by Santamaría *et al.* (2021), though we refer to these samples by their simplified laboratory names herein (see Table 3 for corresponding sample codes used in Santamaría *et al.*, 2021).

Details of the sample collection procedures, *in situ* dose rate evaluations and initial laboratory preparation steps are provided in Santamaría *et al.* (2021). Following initial wet sieving under low-level lighting in the CENIEH Luminescence Dating Laboratory, the samples were transferred to the University of Adelaide for further processing under safe light conditions (605 nm LEDs, <0.15 μW/cm^2 power density at sample position). The most abundant coarse-grain sieved fractions (180–212 μm) were treated with concentrated hydrogen peroxide (H_2O_2) and hydrochloric (HCl) acid to eliminate organics and carbonates, respectively. Quartz grains were then isolated using heavy liquid (LST lithium heteropolytungstate) density ranges of 2.62 g/cm^3 to 2.72 g/cm^3, and subsequently etched with 48% hydrofluoric acid for 40 min to remove the alpha-irradiated external layers. The etched grains were washed in 30% HCl to remove any precipitated fluorides and re-sieved using a 90 μm sieve to eliminate any disaggregated quartz grains and partially etched feldspars.

Single-grain OSL measurements were made using the experimental apparatus described by Arnold *et al.* (2013, 2016), and further detailed in the Supplementary Information. Purified quartz grains with a diameter of 180–212 μm were carefully loaded onto aluminium discs drilled with an array of 300 × 300 μm holes for equivalent dose (D_e) evaluation. Individual D_e values were determined using the single-aliquot regenerative dose (SAR) procedure shown in Table S1, which yielded suitable multiple-grain aliquot and single-grain dose recovery test results for sample LM17188-03 (Fig. S1). Between 2200 and 3600 single-grain D_e measurements were made for each sample (Table S2), with individual D_e values being included in the final age calculation if they satisfied the same quality-assurance criteria employed previously in the Hotel California single-grain OSL study (Arnold *et al.*, 2013), as detailed in the Supplementary Information.

The environmental dose rates for the single-grain OSL samples were estimated using either a combination of *in situ* field gamma spectrometry and low-level beta counting, or *in situ* field gamma spectrometry and inductively coupled

Table 2. Materials and categories of the lithic assemblages from Levels 3 to 7 of the Hotel California archaeological site

Hotel California															
Level 3															
		CATEGORIES													
		nB	1GNBe	Frag 1GNBe	1GNBc	PB	FPB	Frag of PB	2GNBe	2GNBc	Frag 2GNBc	FRAG	INDET	GELIFRACTS	TOTAL
MATERIAL	Neogene flint	7	2	1	-	94	18	85	1	14	2	140	33	35	432 (95.36%)
	Cretaceous flint	3	-	-	-	5	1	1	-	-	-	2	-	-	12 (2.64%)
	Quartzite	2	1	-	1	1	-	-	-	1	-	1	-	-	7 (1.54%)
	Sandstone	2	-	-	-	-	-	-	-	-	-	-	-	-	2 (0.44%)
	TOTAL	14	3	1	1	100	19	86	1	15	2	143	33	35	453
Level 4															
		CATEGORIES													
		nB	1GNBe	Frag 1GNBe	1GNBc	PB	FPB	Frag of PB	2GNBe	2GNBc	Frag 2GNBc	FRAG	INDET	GELIFRACTS	TOTAL
MATERIAL	Neogene flint	1	-	-	-	38	7	26	1	5	2	54	15	18	167 (93.82%)
	Cretaceous flint	3	-	-	-	2	-	1	-	-	-	-	-	1	7 (3.93%)
	Quartzite	-	-	-	-	1	-	-	-	-	-	-	-	-	1 (0.56%)
	Quartz	-	-	-	-	1	-	-	-	-	-	-	-	-	1 (0.56%)
	Sandstone	-	-	-	-	-	-	-	-	-	-	2	-	-	2 (1.12%)
	Total	4	-	-	-	42	7	27	1	5	2	56	-	19	178
Level 5															
		CATEGORIES													
		nB	1GNBe	Frag 1GNBe	1GNBc	PB	FPB	Frag of PB	2GNBe	2GNBc	Frag 2GNBc	FRAG	INDET	GELIFRACTS	TOTAL
MATERIAL	Neogene flint	8	2	1	1	42	7	39	-	8	-	53	6	27	193 (96.01%)
	Cretaceous flint	1	-	-	-	-	1	-	-	-	-	2	-	-	4 (1.99%)
	Quartzite	-	-	-	-	2	-	-	-	1	-	-	-	-	3 (1.49%)
	Sandstone	-	-	-	-	-	-	-	-	-	-	1	-	-	1 (0.49%)
	Total	9	2	1	1	44	8	39	-	8	-	56	6	27	202
LeveL 6															
		CATEGORIES													
		nB	1GNBe	Frag 1GNBe	1GNBc	PB	FPB	Frag of PB	2GNBe	2GNBc	Frag 2GNBc	FRAG	INDET	GELIFRACTS	TOTAL
MATERIAL	Neogene flint	8	1	1	1	45	12	55	1	6	3	92	14	35	274 (93.19%)
	Cretaceous flint	4	-	-	-	2	-	-	-	1	-	9	-	-	16 (5.44%)

(*Continued*)

Table 2. (*Continued*)

LeveL 6

		CATEGORIES													
		nB	1GNBe	Frag 1GNBe	1GNBc	PB	FPB	Frag of PB	2GNBe	2GNBc	Frag 2GNBc	FRAG	INDET	GELIFRACTS	TOTAL
Quartzite	1	-	-	-	1	-	-	-	-	-	-	-	-	2 (0.68%)	
Sandstone	-	-	-	-	1	-	-	-	1	-	-	-	-	2 (0.68%)	
Total	13	1	1	1	49	12	55	1	8	3	101	14	35	294	

Level 7

		CATEGORIES													
		nB	1GNBe	Frag 1GNBe	1GNBc	PB	FPB	Frag of PB	2GNBe	2GNBc	Frag 2GNBc	FRAG	INDET	GELIFRACTS	TOTAL
MATERIAL	Neogene flint	20	2	1	-	51	12	56	-	8	-	79	19	27	275 (86.47%)
	Cretaceous flint	8	-	-	1	7	-	-	-	3	-	13	1	-	33 (10.37%)
	Quartzite	4	-	-	-	2	-	-	1	1	-	2	-	-	10 (3.14%)
	Total	32	2	1	1	60	12	56	1	12	-	94	20	27	318

nB: natural base; 1GNBe: First generation negative base of exploitation; Frag 1GNBe: Fragment of first generation negative base of exploitation; 1GNBc: First generation negative base of configuration; PB: Positive base; FPB: Fragmented positive base; Frag of PB: Fragments of positive base; 2GNBe: Second generation negative base of exploitation; 2GNBc: Second generation negative base of configuration; Frag 2GNBc: Fragment of second generation negative base of configuration; FRAG: Fragment; INDET: Indeterminate.

Table 3. Dose rate data, single-grain equivalent doses and quartz single-grain OSL ages for the Fuente Mudarra samples

						Environmental dose rate (Gy/ka)				Equivalent dose (D_e) data				
Sample name (this study)	Sample name (Santamaría*et al.* 2021)	Strat. level	Depth (m)	Grain size (µm)	Water content [a]	Beta dose rate[b]	Gamma dose rate[c]	Cosmic dose rate[d]	Total dose rate[e,f]	No. of grains[g]	Overdispersion (%)[h]	Age model[i]	D_e (Gy)[e]	OSL age (ka)[e,j]
LM17188-01	ATA 17 FM L4 OSL 17-01	FM4	1.35	180 – 212	19 ± 2	1.14 ± 0.06	0.87 ± 0.05	0.17 ± 0.02	2.22 ± 0.12	207/2300	50 ± 3	CAM	188 ± 8	84.7 ± 5.9
LM17188-02	ATA 17 FM L5 OSL 17-02	FM5	1.55	180 – 212	28 ± 3	1.22 ± 0.06	0.86 ± 0.05	0.16 ± 0.02	2.26 ± 0.12	240/2700	45 ± 3	CAM	202 ± 7	89.2 ± 6.1
LM17188-03	ATA 17 FM L6 OSL 17-03	FM6	1.90	180 – 212	22 ± 2	1.18 ± 0.06	0.88 ± 0.05	0.16 ± 0.02	2.25 ± 0.12	253/3600	35 ± 3	CAM	251 ± 7	111.5 ± 7.2
LM17188-04	ATA 17 FM L7 OSL 17-04	FM7	2.08	180 – 212	22 ± 2	1.17 ± 0.05	0.92 ± 0.05	0.15 ± 0.02	2.28 ± 0.12	187/2200	32 ± 3	CAM	264 ± 9	116.2 ± 7.5
LM17188-05	ATA 17 FM L8 OSL 17-05	FM8	2.50	180 – 212	22 ± 2	1.23 ± 0.06	0.91 ± 0.05	0.15 ± 0.02	2.32 ± 0.13	249/2300	32 ± 3	CAM	276 ± 8	119.2 ± 7.6

[a] Long-term estimated water content, expressed as % of dry mass of mineral fraction, with an assigned relative uncertainty of ±10%.

[b] Beta dose rates were calculated on dried and powdered sediment samples using a Risø GM-25-5 low-level beta counter (Bøtter-Jensen and Mejdahl, 1988) for samples LM17188-01, -03 and -05, and using a combination of inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma optical emission spectrometry (ICP-OES) for samples LM17188-02 and -04. Radionuclide concentrations and specific activities of beta counting standards have been converted to dose rates using the conversion factors given in Guérin *et al.* (2011), making allowance for beta dose attenuation due to grain-size effects and hydrofluoric etching (Mejdahl, 1979; Brennan, 2003).

[c] Gamma dose rates were calculated from *in situ* measurements made at each sample position with a $LaBr_3$:Ce detector using the 'energy windows' method detailed in Arnold *et al.* (2012b) and Duval and Arnold (2013). Radionuclide concentrations and specific activities of gamma spectrometry calibration materials, and K, U, Th concentrations determined from the field gamma-ray spectra have been converted to dose rates using the conversion factors given in Guérin *et al.* (2011).

[d] Cosmic ray dose rates were calculated using the approach of Prescott and Hutton (1994) and assigned a relative uncertainty of ±10%.

[e] Means ± total uncertainty (68% confidence interval), calculated as the quadratic sum of the random and systematic uncertainties.

[f] Includes an internal dose rate of 0.03 Gy/ka with an assigned relative uncertainty of ±30%, based on intrinsic ^{238}U and ^{232}Th content published by Mejdahl (1987), Bowler *et al.* (2003), Jacobs *et al.* (2006), Pawley *et al.* (2008) and Lewis *et al.* (2020), and an *a*-value of 0.04 ± 0.01 (Rees-Jones, 1995; Rees-Jones and Tite, 1997). Intrinsic radionuclide concentrations and specific activities have been converted to dose rates using the conversion factors given in Guérin *et al.* (2011), making an allowance for beta dose attenuation due to grain-size effects (Mejdahl, 1979).

[g] Number of D_e measurements that passed the single-aliquot regenerative-dose rejection criteria and were used for D_e determination/total number of grains analysed.

[h] The relative spread in the D_e dataset beyond that associated with the measurement uncertainties of individual D_e values, calculated using the central age model.

[i] Age model used to calculate the sample-averaged D_e value for each sample. The choice of age model for each sample has been made on statistical grounds using the maximum log likelihood score (L_{max}) criterion outlined by Arnold *et al.* (2009). CAM = central age model.

[j] Total uncertainty includes a systematic component of ±2% associated with laboratory beta-source calibration.

plasma mass spectrometry (ICP-MS)/inductively coupled plasma optical emission spectrometry (ICP-OES), taking into account cosmic ray contributions (Prescott and Hutton, 1994), an assumed minor internal alpha dose rate (Bowler *et al.*, 2003), beta dose attenuation and long-term water content (see Table 3 and Supplementary Information). Where possible, environmental dose rates have been calculated from the same field gamma spectrometry and beta counting datasets used by Santamaría *et al.* (2021). However, as detailed in the Supplementary Information, it was necessary to calculate alternative beta dose rates for LM17188-02 and LM17188-04 using ICP-MS/OES data because of ambiguities with the original beta counting datasets for these samples.

The proportions for long-term water content adopted by Santamaría *et al.* (2021) (38–56% dry weight) are significantly higher than those reported or typically assumed for well-preserved silty clay deposits in northern Iberia's open-air localities (e.g. Moreno *et al.*, 2012; Arnold *et al.* 2013, 2016; Méndez-Quintas *et al.*, 2018; Rios-Garaizar *et al.*, 2022). These assumed values are also higher than the measured water content values of freshly preserved silty clay deposits inside the deeper and closed parts of the Atapuerca endokarst system (Arnold *et al.*, 2014, 2015; Demuro *et al.*, 2014, 2019a, 2019b, submitted). To ensure consistency with these previous publications, including the single-grain OSL study performed at Hotel California, we have therefore adopted more conservative long-term water content proportions of 19–28% dry weight (equivalent to 30% of the present-day saturated water content estimates), which overlap with the Hotel California long-term water content estimates of 14–26% dry weight at 2σ (see Supplementary Information for further details).

Results

Level 3

A total of 453 items of lithic production were recovered in the excavation of Level 3 (see Table 2). The most abundant material in the set is Neogene flint, with 95.36% of the items made from this material, followed by Cretaceous flint (2.64%), quartzite (1.54%) and sandstone (0.44%). Different studies of raw materials carried out by the research team in the Sierra de Atapuerca, identified the macro, micro and compositional characteristics of the two types of flint found at this site (García Antón, 2016, 2018). In addition, we have more specific studies in which we have already included samples from Hotel California (Navazo *et al.*, 2008). It is relatively easy to find pieces of Neogene flint affected by patinas in the open-air landscapes of the Sierra de Atapuerca, with different colorations that range from white to orange and even grey and black. The patinas are determined by the sediment that sometimes contains iron oxide, staining the pieces with orange tones, and sometimes black due to contact with manganese. In Level 3, 77.5% ($n = 335$) of the pieces of Neogene flint had a white patina; 19.2% ($n = 83$) had an orange patina; 1.8% ($n = 8$) had grey patinas; and 0.6% ($n = 3$) black patinas.

Post-depositional processes are probably behind the proportion of fragments (31.56%) and gelifracts (7.72%) found at the site. We also found a conjoin connection of a flake's old fracture, with a 20 cm horizontal distance between both fragments (Fig. 2e).

There were 14 natural bases (3% of the assemblage). Half of them ($n = 7$) were of Neogene flint. These are blocks or fragments of raw material that come from the secondary deposits, fractured and naturally disaggregated from the primary outcrops. The sizes of the Neogene flint natural base (nB) vary from $46 \times 34 \times 33$ mm to $180 \times 155 \times 140$ mm. Four of them appear tested, so that a pair of flakes were extracted in a unifacial longitudinal or bifacial orthogonal direction, and were then abandoned.

Exploitation

Different methods of exploitation are reflected in the presence of three first-generation negative bases of exploitation (1GNBe), one second-generation negative base of exploitation (2GNBe) and a fragment of 1GNBe which was later retouched. The first of the cores that are complete (ATA'08/HC3/K23/21) was exploited over a natural fragment of Neogene flint of $92 \times 76 \times 60$ mm, with the knapper making use of the natural edges to produce two opposing surfaces. The first shows longitudinal unipolar exploitation with a flat angle and deep extractions that generated flakes (positive base; PB); the largest of which was 38×50 mm. The second face converges laterally at an approximately 90° angle to the direction of the removals on the first face. This second face is less exploited, its longitudinal unipolar extractions are of flat angles, and the largest is 26×13 mm. The exploitation system employed on this base is bifacial orthogonal exploitation in its initial stage (Fig. 2b).

In the case of HC'06/N1/K22/15, we have a core exploited over a Neogene flint nB of $74 \times 67 \times 30$ mm. The core shows bifacial exploitation, with two faces having centripetal extractions; one being the exploitation face and the other the preparation face. Face 1 presents very deep removals in all of the core's perimeter (4C), which were extracted at an angle of around 25° to 5°. The last removal on this face is 41×39 mm. The second face also has deep scars across the perimeter (4C), but they do not cover the entirety of the face, for there is an unexploited zone in the centre that coincides with where the flint is grainier, has impurities and is of a lower quality. This face's removals have angles between 60° and 80°, and the size of the removals is much smaller, between 14 and 26 mm long. The core's perimeter has a low sinuosity. It is a bifacial centripetal asymmetrical hierarchical core, with a centripetal exploitation displaying parallel planes (Levallois). The core was in a phase of exploitation, with very little overlap between removals, which are pretty large, while the faces are prepared for exploitation (Fig. 2b).

The last of the complete 1GNBe found in this level is of quartzite (ATA'07/HC03/H22/21). It measures $103 \times 116 \times 44$ mm and is exploited on both sides, making use of the longer and wider surface of the base. Exploitation is peripheral, with a centripetal direction on secant planes. The exploited perimeter of the first face (4C) has removals with angles that vary between 25° and 60° that are deep without covering the entire surface. The sizes of the products vary between 44×32 mm and 23×22 mm. The perimeter of the second face is not fully intervened (3C), scars have angles of between 35° and 75° and deep removals. The sizes of the products on this face range from 40×62 mm to 9×15 mm. The core was in an early phase of exploitation, with both faces still conserving some cortex. The edge that separates both faces is sinuous, the faces are non-hierarchical and there are no visible signs of preparation. The exploitation system is bifacial centripetal symmetrical non-hierarchical (discoid) (Fig. 2a).

In Level 3, we have one 2GNBe of Neogene flint, that is, the exploited base is one flake (PB). ATA'08/HCO3/K23/15, $71 \times 67 \times 41$ mm, has bifacial exploitation, and both its faces have bipolar orthogonal extractions, 2C and a flat angle. The largest removals measure 55×36mm and 36×47mm (Fig. 2d).

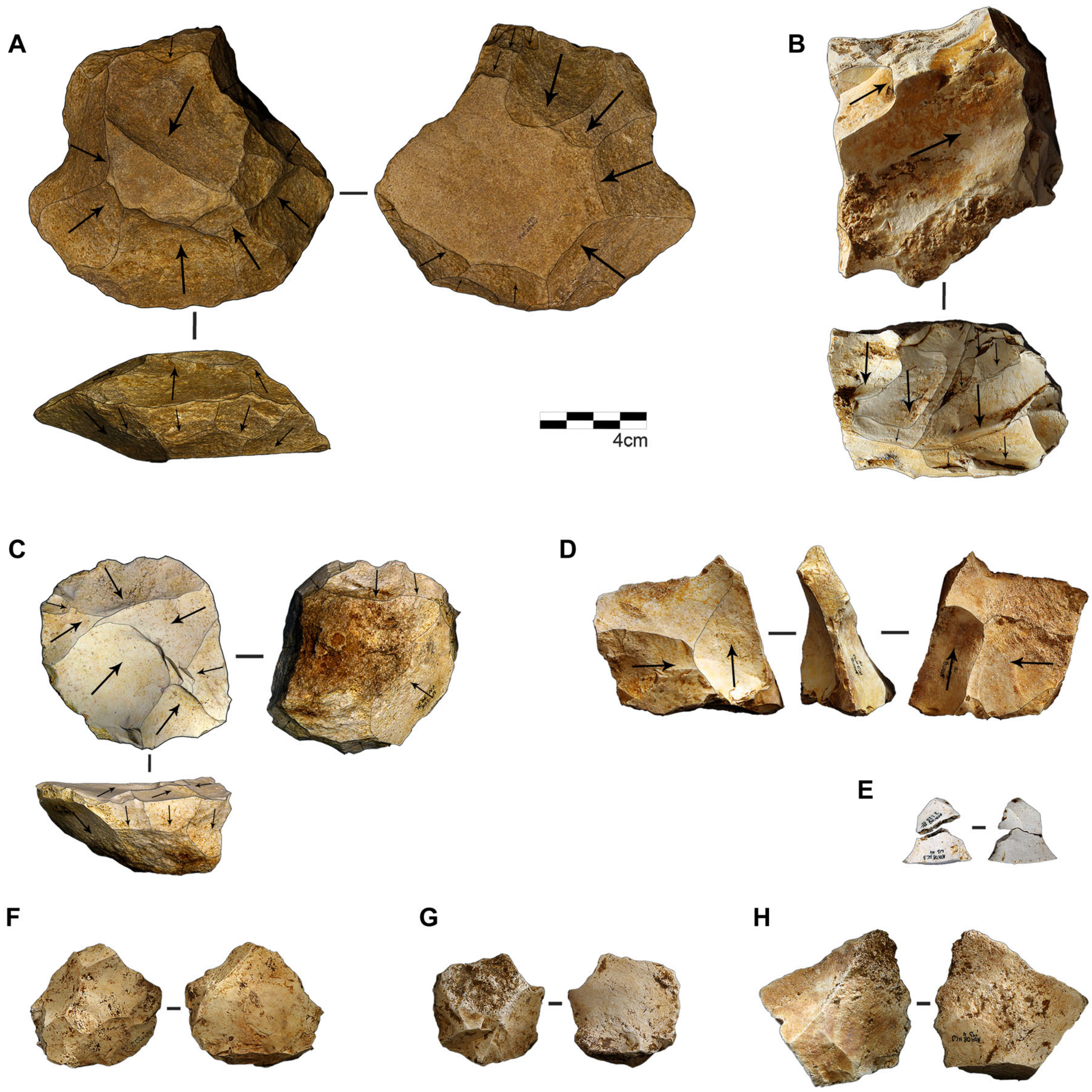

Figure 2. Lithic items from Hotel California Level 3: Cores: 1GNBe (A–C) and 2GNBe (D). Conjoin (E). Examples of centripetal and chordal exploitation blanks. A1 type (F–G). A2 type (H). [Color figure can be viewed at wileyonlinelibrary.com]

Level 3 also has 100 complete PBs, which, added to the 19 fragmented positive bases (FPBs) and 86 Frag of PBs, make up 45.25% of the assemblage. The flakes have an average length, width and thickness of 34 × 32 × 13 mm.

The complete PBs show us that the assemblage is characterised by diffuse bulbs (76.8%) of convex morphology (91.9%), non-cortical butts (94.9%) and platform surfaces (84.8%) of trapezoidal (35.4%) or triangular morphology (32.3%), unifaceted (85.9%) and with straight delineation (51.5%). The dorsal face is mostly non-cortical (96%), has between three and four previous scars (26.3% and 22.2%) and uniangular delineation (47.5%).

We have determined that 34 of the complete 100 PBs belong to type A1; nine to type A2, and one to B2, which reflects a broad exploitation of centripetal/chordal peripheral cores of secant planes (Fig. 2f–h) and a low presence of parallel planes.

Configuration

There is one first-generation negative base of configuration (1GNBc), a quartzite pebble tool with a small unifacial edge (1C) with an abrupt angle and continuous and convex retouches (Fig. 3a).

In the case of retouched flakes, the chosen pieces were larger than the average PB, keeping in mind that the 2GNBc had an average size of 55 × 50 × 20 mm. Fifteen 2GNBc and two frag 2GNBc were recovered from this level, among which there are seven sidescrapers (four simples (Fig.3e), one convergent (Fig. 3f), two fragments of sidescrapers and one configured over a core flank; Types R1, R22 and R23), four notches (D21) (Fig. 3g), two denticulates (Fig. 3b), one denticulate/Tayac point (Fig. 3c) (D1 and D24), one endscraper (G21) (Fig. 3h), one bec (Bc1) (Fig. 3d) and one abrupt (A2).

Level 4

This level has 178 lithic artefacts, of which 93.82% are of Neogene flint. The rest of the raw materials used are Cretaceous flint (3.93%), quartzite (0.56%), quartz (0.56%) and sandstone (1.12%). Some 72.5% of the Neogene items (129) have a white patina, while 35 pieces (19.6%) have an orange patina and only two are grey.

We found a large Neogene flint nB (158 × 112 × 58 mm), as well as three small nodules of Cretaceous flint (with an average size of 32 × 21 × 17 mm), one of which showed signs of testing.

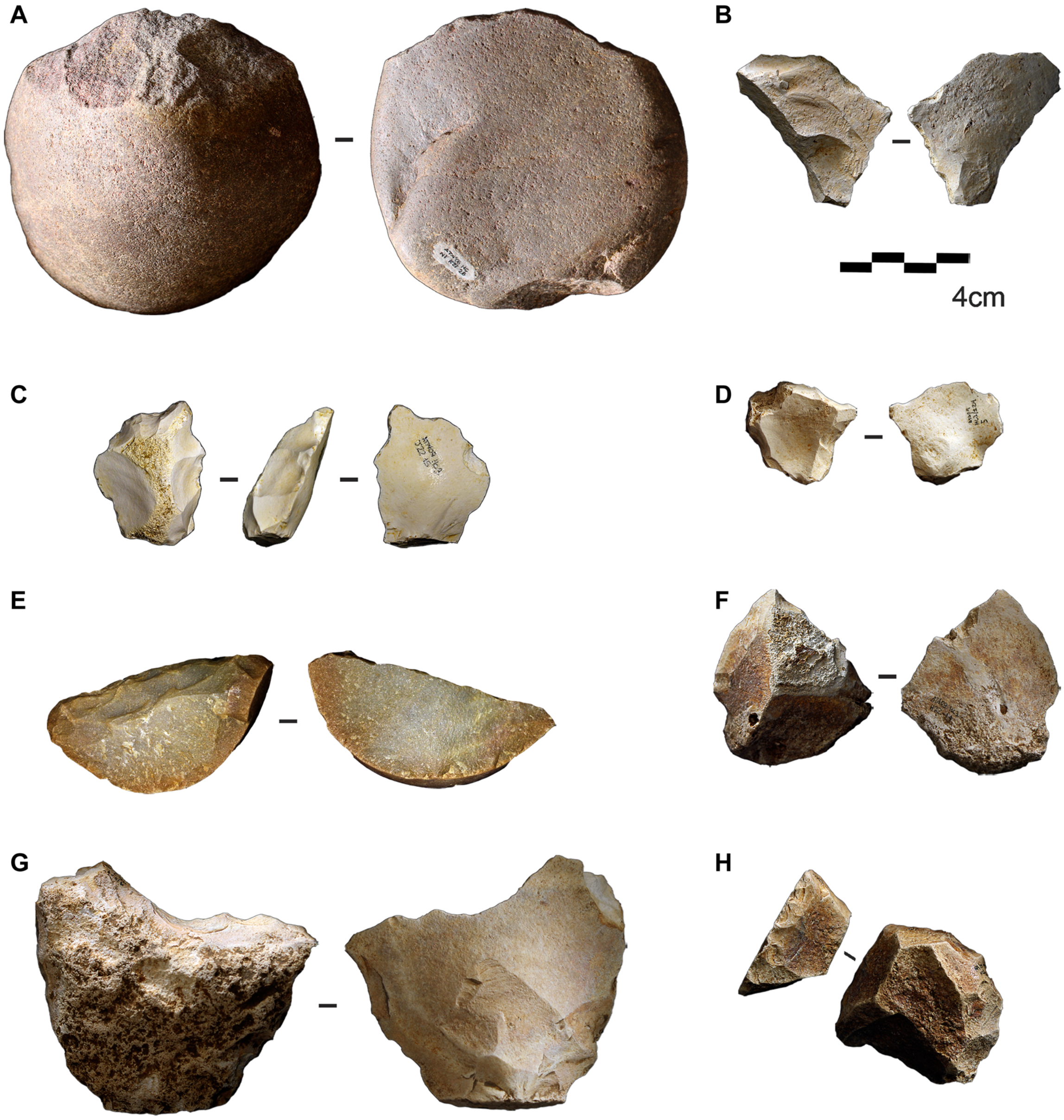

Figure 3. Lithic items from Hotel California Level 3: Retouched items: 1GNBc: pebble tool (A) and 2GNBc (B–H): denticulate (B), Tayac point (C), bec (D), sidescraper (E), convergent sidescraper (F), notch (G), end scraper (H). [Color figure can be viewed at wileyonlinelibrary.com]

Exploitation

This level has produced only one 2GNBe, a core on flake with a surface alteration, sized 62 × 68 × 34 mm, that presents two convergent removals on the dorsal face and that appears to have been abandoned in an early stage of exploitation (Fig. 4a). To identify the exploitation methods used in this level, we have had to study their products: 42 PB that comprise 23.59% of the assemblage. These have similar characteristics to those of Level 3; flakes with an average size of 27 × 27 × 10 mm, with unifaceted platform butts and dorsal faces with 3/4 scars and uniangular delineation. Of these 42 PBs, nine correspond to type A1 (Fig. 4b–c) and one to A2 (Fig. 4d), reflecting centripetal and chordal exploitations of secant planes; and one PB is of type B1, produced by a centripetal/chordal exploitation of parallel planes.

Configuration

Retouched items (2GNBc) are larger than the average PB, with dimensions of 47 × 34 × 15 mm. They are of the following types: two notches (D21) (Fig. 4h), one denticulate (D1) (Fig. 4f), one abrupt (A2), sidescraper + bec (R21+Bc1) (Fig. 4g), and a frag BN2Gc of notch (D21) (Fig. 4e) and denticulate (D1).

Level 5

Level 5 has 202 lithic items, 96% of which are of Neogene flint. Quartzite, Cretaceous flint and sandstone are present at percentages below 2%. The most represented category is that of fragments (27.9%). Categories associated with flakes: PB (21.9%), FPB (4%) and Frag of PB (19.4%) comprise 45.3% of the assemblage. Since the assemblage is mostly composed of fragmented elements – fragments, FPB and Frag of PB – its conservation is poor. Moreover, gelifracts account for 13.4%, which resulted from the exposure of these items to cold conditions at the surface. Some 39.3% of the items display gelifraction scars on their surface, and we have identified 13 gelifraction domes and 14 gelifraction splinters. Regarding the patinas on the Neogene flint items, 61% were white ($n = 119$), 36% were orange ($n = 71$) and 1% was grey ($n = 2$).

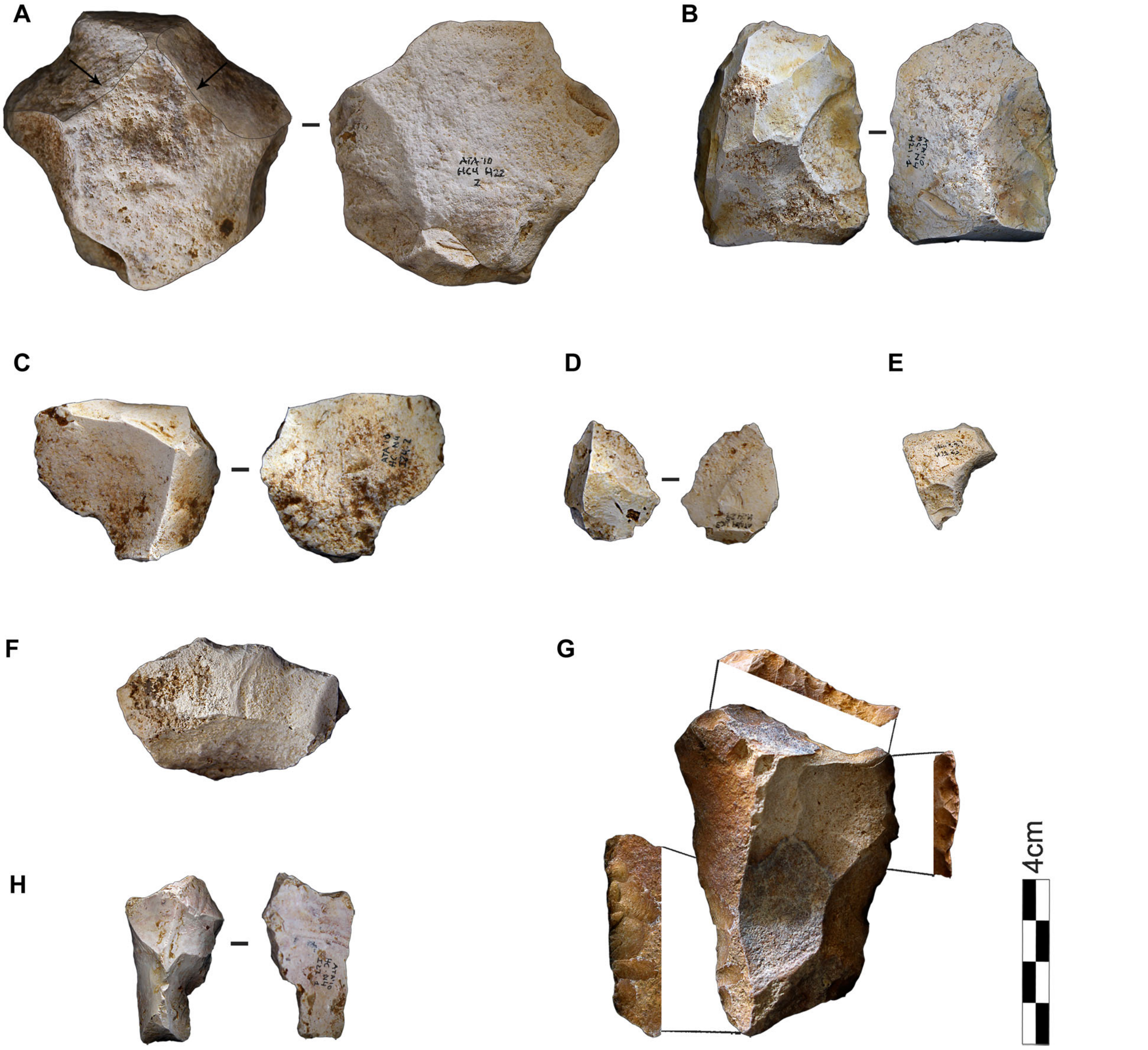

Figure 4. Lithic items from Hotel California Level 4: Cores: 2GNBe (A). Examples of centripetal and chordal exploitation blanks. A1 type (B–C). A2 type (D). Retouched items: 2GNBc (E–H), retouched fragment (E), denticulate (F), sidescraper with bec (G) and notch (H). [Color figure can be viewed at wileyonlinelibrary.com]

There are eight Neogene flint nB, with sizes that vary from 56 × 44 × 32 mm to 123 × 70 × 56 mm. These have surface gelifraction scars and they are of a low quality, for the flint is coarse-grained, with geodes and intrusions. Perhaps this is why it was not exploited. There is a single Cretaceous flint nB in this level, which measures 33 × 28 × 18 mm, is of good quality and displays evidence of test removals.

Exploitation

This level's first 1GNBe is large and of Neogene flint. ATA'08/HC04/J23/9 measures 138 × 101 × 81 mm. It is in an early stage of exploitation, and there are a few removals, which are longitudinal, unifacial and unipolar with secant extraction planes. It is difficult to identify the exploitation system because the core has been rounded, its volume being significantly altered and its surfaces degraded (Fig. 5b).

The second 1GNBe of Neogene flint (ATA'08/HC04/J23/3) has a size of 110 × 91 × 85 mm. It is exploited bifacially, making use of the base's larger surfaces. The exploitation is evident in half the perimeter on both sides. The first face has only a small part of the exploited contour (1C), with deep longitudinal removals that approach 65°. The second face is exploited in 1C, with converging removals of a flat angle (15°) that are quite deep in respect to the surface. It is in an early stage of exploitation that could be regarded as bifacial orthogonal (Fig. 5a). We also documented a 1GNBe fragment of 74 × 57 × 32 mm, which seems to correspond to a discoid type.

Exploitation products have an average size of 42 × 38 × 14 mm. Forty-four are complete. Two of them are of quartzite and the rest of Neogene flint. The Neogene flint PB have bulbs (mostly diffuse and convex), non-cortical platform type butts, are unifaceted and straight, with non-cortical dorsal faces and several previous scars with uniangular delineation. The two quartzite flakes are somewhat larger (55 mm maximum length). They have tiny remains of cortex in the butt or dorsal face, and seem to have been produced by centripetal schemes.

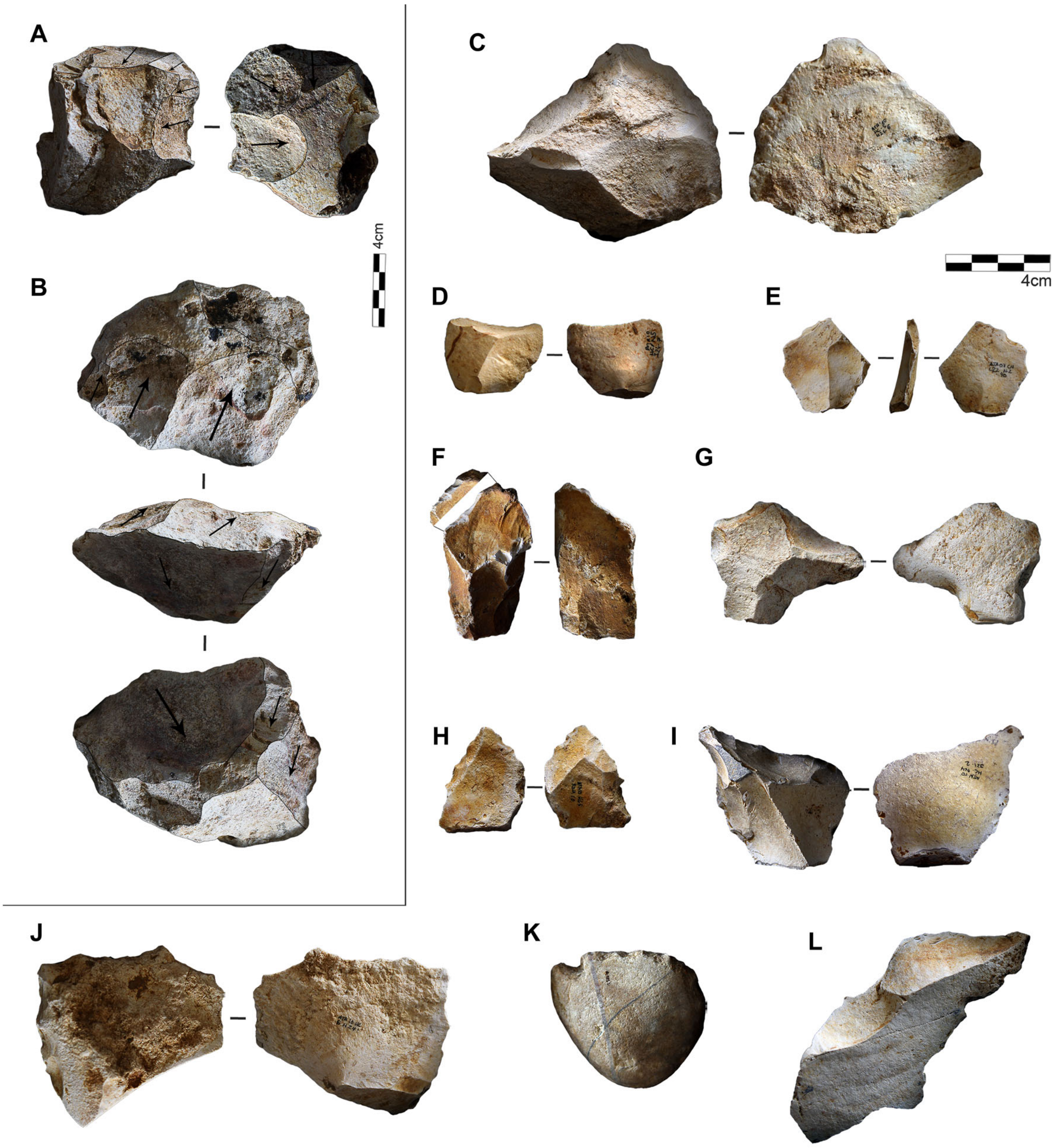

Figure 5. Lithic items from Hotel California Level 5: Cores: 1GNBe (A–B). Examples of centripetal and chordal exploitation blanks. A1 type (C–D). B1 type (E). Retouched items: 2GNBc (F–L), sidescraper with double patina (F), notches (G), denticulate point with bifacial retouch (H), Tayac point (I), abrupt (J), sidescraper (K), retouched fragment (L). [Color figure can be viewed at wileyonlinelibrary.com]

We have been able to determine the exploitation system of 12 of the 44 flakes: eight correspond to type A1 (Fig. 5c–d), three to A2 and with B1(Fig. 5e).

Configuration

The configured items include a 1GNBc. It is a retouch on a fragment of Neogene flint in which an edge was retouched with two notches, on the side of a trihedron (Fig. 5l).

The 2GNBc are configured on similarly sized PB, with an average size of 46 × 49 × 20 mm. In this level we have nine BN2Gc, eight of which are of Neogene flint and one of quartzite. This latter item is a completely cortical flake in which a sidescraper is configured in the transversal distal (R22) through a direct semi-abrupt and marginal retouch (Fig.5k).

Of the eight Neogene flint tools, four are notches D21 (three are configured on the PB's right side) (Fig. 5g), sidescraper with double patina (Fig. 5f) one denticulate point with bifacial retouch (Fig. 5h), one Tayac point (Fig. 5i) (D24) and one abrupt (A1) (Fig. 5j).

Level 6

We have recovered a total of 294 lithic artefacts from Level 6, of which 93.1% correspond to pieces of Neogene flint. This continues to be the predominant material in the entire sequence because it is easily obtained in this area. It is followed by Cretaceous flint (5.44%) and smaller amounts of other materials, such as quartzite (0.68%) and sandstone (0.68%). Fragmented elements are also abundant (nearly 30% of items found in all levels belong to this category), as are gelifraction scars, present in 50% of the Neogene flint items. Some 61% of Neogene flint items have a white patina ($n = 167$), 34% have an orange patina ($n = 9$), 3% a grey patina ($n = 9$) and 0.3% have a black patina ($n = 1$).

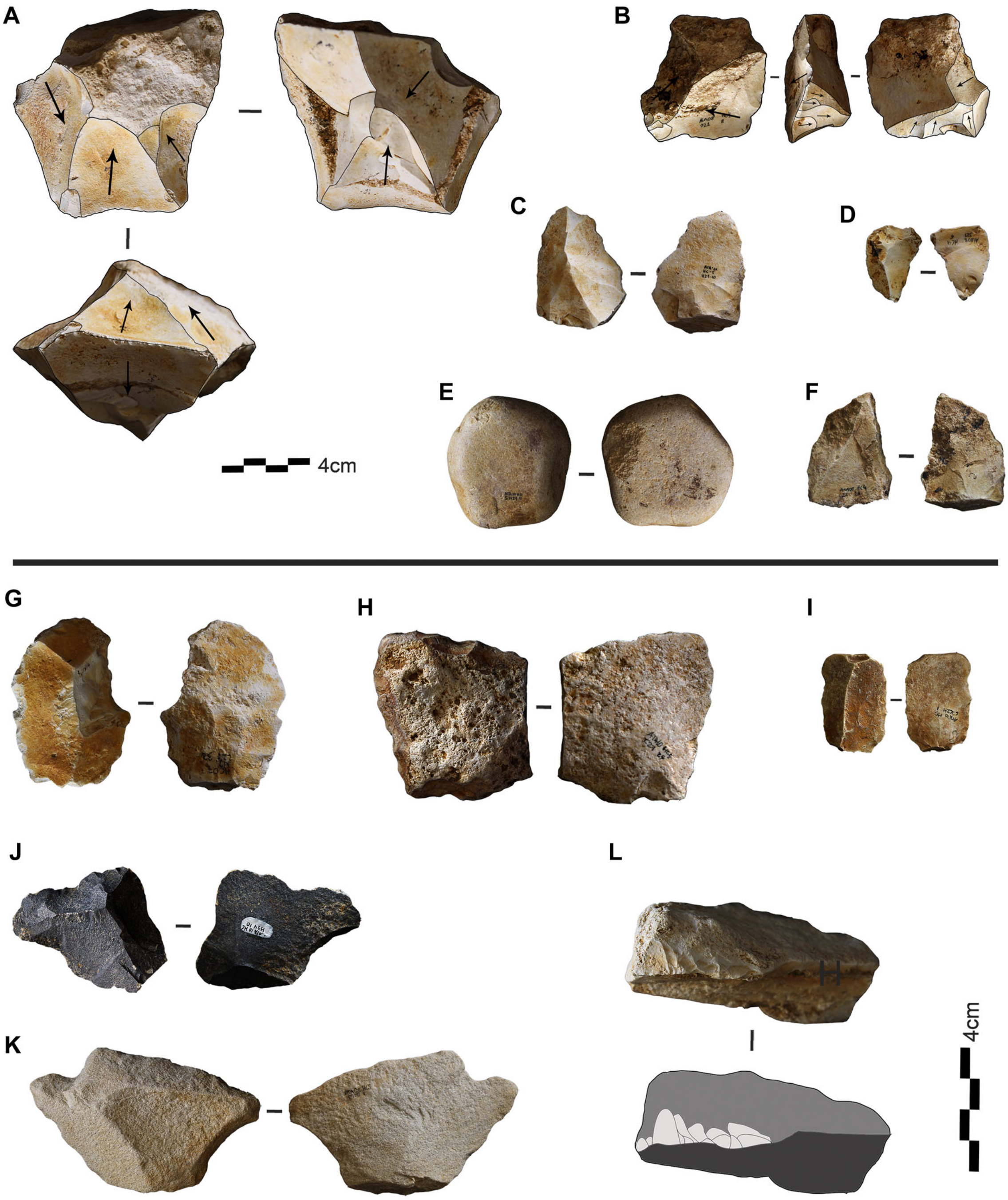

Figure 6. Lithic items from Hotel California Level 6: Cores: 1GNBe (A) and 2GNBe (B). Examples of centripetal and chordal exploitation blanks. A1 type (C–D). A2 type (F). Natural base: hammer (E). Retouched items: 2GNBc (G–L): denticulate with double patina (G), Tayac point (H), side scraper (I), denticulate with black patina (J), notch (K), and retouched fragment – endscraper (L). [Color figure can be viewed at wileyonlinelibrary.com]

The various nB of this level are diverse in terms of raw material: eight are of Neogene flint, four of Cretaceous flint and one of quartzite. The Neogene flint nB are large, the biggest measuring 160 × 122 × 48 mm, but they are still fragments that came off or were extracted from the outcrop, and do not conserve cortex, even though near the site, primary Neogene outcrops have a metrical character. The Cretaceous flint nB are small pebbles with an average size of 19 × 13 × 12 mm that conserve cortical surfaces. One of the four was clearly tested on two faces in a unipolar longitudinal fashion. The only quartzite nB of the assemblage measures 60 × 59 × 32 mm and one of its ends has a desquamation, perhaps as a result of a percussive impact received when being introduced to the knapping process as a hammerstone (Fig. 6e).

Exploitation

Regarding exploitation systems, in this level we have one 1GNBe, one frag 1GNBe and one 2GNBe, all of Neogene flint.

Among the Neogene flint cores is one 1GNBe, HC09/N4/K20/1, on a 104 × 87 × 67 mm fragment. The part of the base's perimeter that has an adequate angle for knapping was exploited bifacially and centripetally, while the zone of the base fracture is pretty thick and vertical (67 mm) and remained unexploited, so that the item presents a half-peripheral exploitation. The first face has deep simple angle removals (35°) that comprise 2C of the core's perimeter. The second face displays knapping fractures associated with intrusions in the flint that apparently deflected the fracture planes, and are the likely cause for the base being abandoned. The few removals on it are of a simple angle (45°) and deep. Both faces converge symmetrically, with a centripetal conception of secant planes and a bifacial symmetrical non-hierarchical exploitation (Fig. 6a).

ATA08/HC/N4/J21/8 is an exploited core on a Neogene flint PB that measures 54 × 52 × 26 mm. The PB is bifacially exploited and its size is 40 × 34mm. Face 1 presents a very deep removal (1C) extracted at an angle between 40° and 15° with respect to the edge. The second face has scars only on one part of the perimeter (1C), and they are shallow and small (20 × 12 mm) in the half peripheral. These removals are centripetal and have angles between 75° and 80°. The core's contour has a low sinuosity. This bifacial centripetal, asymmetrical, non-hierarchical core is in a full phase of exploitation (Fig. 6b).

Finally, among the Neogene items is ATA10/HC/N6/L24/3, a large fragment of 1GNBe (87 × 65 × 55 mm) derived from a discoidal scheme of initial exploitation that has fractured.

The PB also indicate the exploitation systems used by the Neanderthal knappers. Eleven of the 45 Neogene flint PB have been identified as type A1 (Fig. 6c–d) and two as type A2 (Fig. 6f), which are related to centripetal and chordal exploitations of secant planes. They have an average size of 40 × 36 × 13 mm. Forty-five are of Neogene flint, two of Cretaceous flint, one of quartzite and one of sandstone. These flakes follow the model of those in the previous levels: they predominantly have convex and diffuse bulbs, non-cortical platform butts, are unifaceted and straight, with non-cortical dorsal faces and several previous scars with uniangular delineation.

Configuration

The retouched tools found in this level are for the most part 2GNBc, and the average size of the flakes chosen for retouch is somewhat larger than that of the average PB, at 46 × 54 × 17 mm. Among them, denticulates (D1) stand out, four of which are complete (one with an intense black patina (Fig. 6j) and another with double patina (Fig. 6g)) and two that are frag BN2Gc. We also have a complete sidescraper (R21) (Fig. 6i), a Tayac point (D24) (Fig. 6h), a notch (D21) in a Neogene flint fragment and another on a sandstone PB (Fig. 6k) and, finally, an endscraper (G11) configured on a great fragment of Neogene flint (Fig. 6l).

At 5.44%, the percentage of Cretaceous flint was higher in this level than in the others. This percentage is distributed among 14 items, of which four are the aforementioned nB, two PB, nine fragments and one retouch item configured on a fragment of this same material, for which an abrupt and continuous retouch was carried out, making use of the right angle of a fractured zone.

Level 7

A total of 318 items have been recovered from Level 7. The most abundant raw material is still Neogene flint, but in a lower percentage; only 86%. This is followed by Cretaceous flint (10%) and quartzite (3%). Some 47% of the Neogene flint items have a white patina ($n = 130$); 40% have an orange patina ($n = 111$), and there are sporadic grey patinas (6%, $n = 17$) and black (2%, $n = 7$).

The proportions of fragments (29%) and gelifracts (8%) is large. We also found a conjoin connection fracture of a PB (Fig. 7g).

There is also an abundance of large nB. Of the 32 nB, 20 are of Neogene flint and have an average size of 155 × 120 × 66 mm. One of them is tested (ATA10/HC07/K24/14). At 89 × 67 × 43 mm, it has orthogonal bifacial removals on one of its ends, in a small area from which only five PB were extracted before being abandoned.

The four quartzite nB are also large. At an average size of 114 × 90 × 53 mm, they are river pebbles that for the most part have natural fractures, although one appears to have been used as a hammerstone (Fig. 7h).

The Cretaceous nB are smaller. They appeared naturally in their primary outcrops like nodules with rounded contours. Seven of the eight Cretaceous nB that we found have an average size of 31 × 24 × 18 mm, while one of them, even though it is fractured, stands out above the rest for its larger size (132 × 75 × 63 mm). It is a good quality Cretaceous flint with many gelifraction scars in the cortical area (Fig. 7i).

Exploitation

The 1GNBe with more advanced exploitation tend to centripetal schemes. As an example, there are large bases like ATA08/HC05/J21/9, which measures 137 × 104 × 94 mm and which was exploited on only one of its surfaces, with unifacial centripetal scars of secant planes, a flaking angle of 70° and deep removals that occupy 3C of the piece's actual perimeter. This 1GNBe suffered a fracture in the early phase of its exploitation (Fig. 7a).

A similar example is ATA07/HC02/L22/49, a base measuring 117 × 83 × 67 mm that is exploited only in its most abrupt face, with a peripheral unifacial exploitation in a centripetal direction of secant planes. The totality of the perimeter is exploited (4C) with removals whose angles are approximately 75° all across the exploited surface. The sizes of the products vary between 40 × 28 mm and 25 × 22 mm. The base was abandoned in an intermediate stage of exploitation (Fig. 7b).

We found only two 1GNBe fragments of Neogene flint in this level, and both seem to be derived from centripetal exploitation of secant planes.

There was also a quartzite 2GNBe. The core was first exploited on a Frag of PB, for which the ventral face served as the face of exploitation and the dorsal is completely cortical. The face has centripetal removals all across the core's perimeter (4C), which are deep and are extracted at an angle between 45 and 55°. The exploitation on this core follows a unifacial centripetal secant planes scheme (Fig. 7c).

The 60 positive bases have an average size of 40 × 40 × 14 mm and have the following attributes: diffuse and convex bulbs, non-cortical platform butts, unifaceted and straight, with non-cortical dorsal faces, with three to four previous scars, and uniangular delineation, which make them similar to those in the previous levels.

We have been able to identify the origin exploitation of 14 of the 51 Neogene flint PB found: 10 of them are type A1 (centripetal of secant planes) (Fig. 7d–e) and four are type A2 (chordal of secant planes) (Fig. 7f), coinciding with the type of exploitations that we saw in the cores.

Configuration

Regarding the configured tools, all those of Neogene flint were configured on PB, with sizes that vary greatly. Most of the eight Neogene 2GNBc are small, but they are still larger than the average size of those found in previous levels (51 × 46 × 18 mm), and two are much larger, approximately 100 mm in length. The types generated are mostly sidescrapers (5). One of these pieces also has an abrupt retouch with rounding on its surfaces (R22+A1). Another, one of the larger items, is a PB that conserves cortex and is derived from a centripetal core. It is very thick and irregular, and has a very clear double patina retouch (R21) (Fig.8b). A third sidescraper, also of large format,

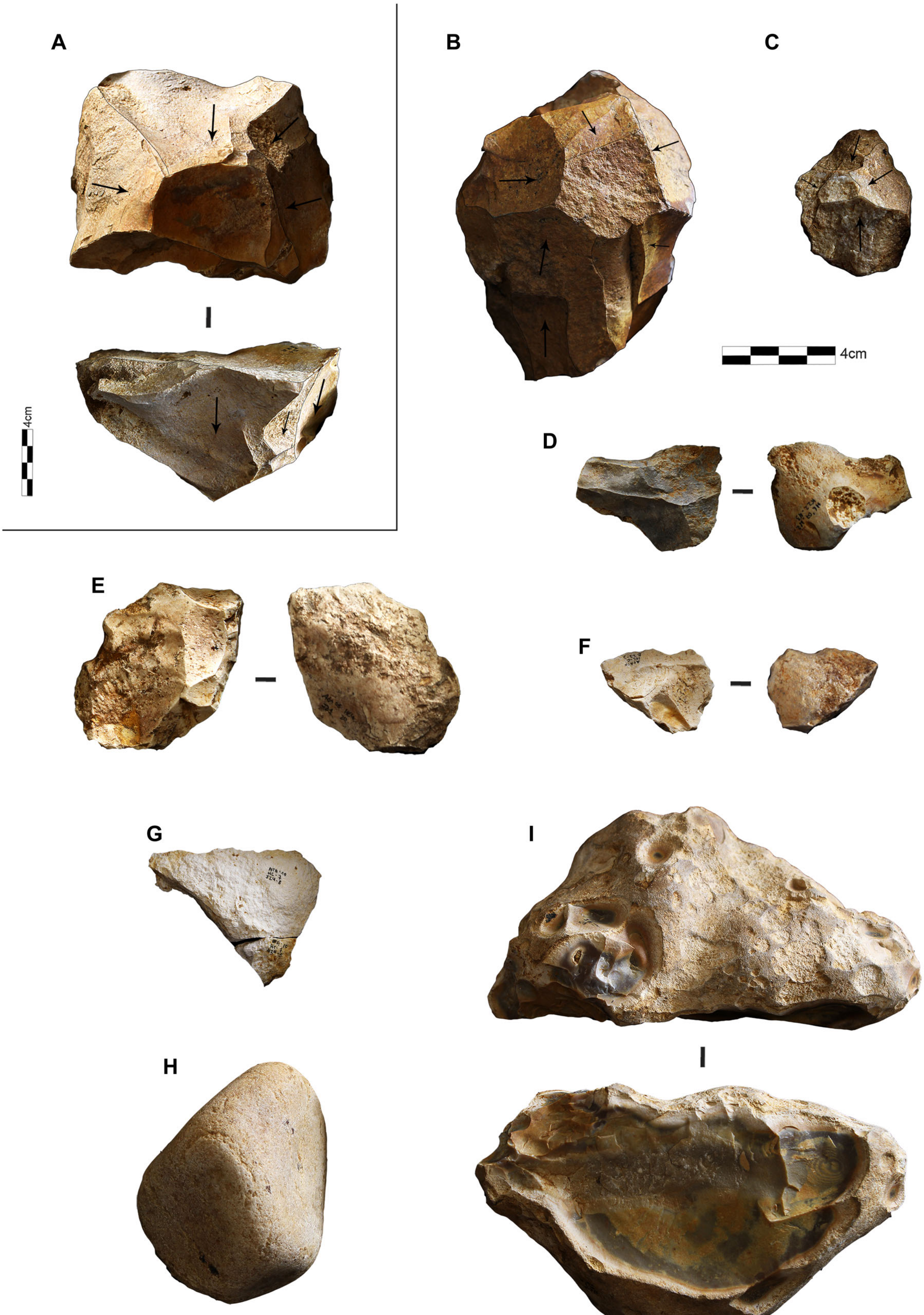

Figure 7. Lithic items from Hotel California Level 7: Cores: 1GNBe (A–B) and 2GNBe (C). Examples of centripetal and chordal exploitation blanks. A1 type (D–E). A2 type (F). Conjoin (G). Natural base: possible hammer (H), Cretaceous Flint NB with gelifraction scars (I). [Color figure can be viewed at wileyonlinelibrary.com]

is a transversal sidescraper whose retouch does not encompass the whole edge (R22), in addition to R23 (Fig.8d) and D23 (Fig. 8a). There are also three notches configured via several strikes on thick pieces (D21) (Fig. 8c).

The Cretaceous 2GNBc (3) are of varied sizes, and they are: a bec associated with a denticulate that is 58 × 33 × 15 mm (D3+Bc1) (Fig. 8g); a notch on a Janus flake (D21); and a sidescraper (both of these are less than 30 mm). Among the

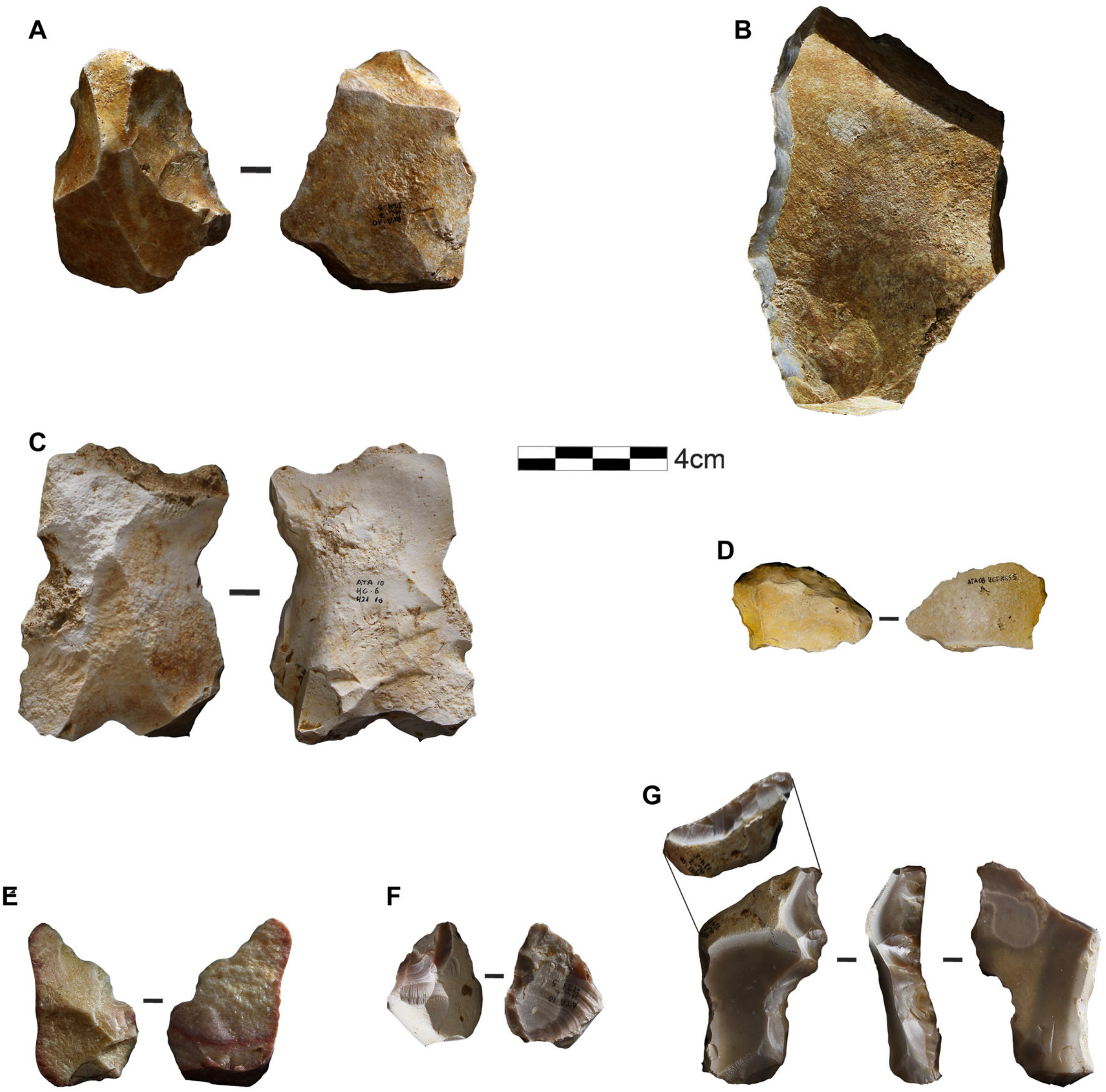

Figure 8. Lithic items from Hotel California Level 7: Retouched items: 2GNBc (A–G): denticulate sidescraper (A), sidescraper with double patina (B), notch (C), sidescraper (D), denticulate on quartzite (E), sidescraper on Cretaceous pebble (F) and denticulate with bec (G). [Color figure can be viewed at wileyonlinelibrary.com]

Cretaceous tools, there is also a fractured natural pebble retouched as a sidescraper (R1) (Fig. 8f).

Finally, we have recovered a quartzite denticulate (D1) configured on a cortical and debordant flake of very fine grain, which measures 42 × 28 × 12 mm (Fig. 8e).

Single-grain OSL dating of Fuente Mudarra

Table 3 summarises the environmental dose rates, single-grain D_e values and final ages obtained for the Fuente Mudarra OSL dating samples. After adopting more regionally representative estimates of long-term water content and addressing some practical constraints with the original datasets, the revised dose rate estimates of these samples are 22–36% higher than those reported by Santamaría *et al.* (2021) and are in agreement with the dose rates reported for the Hotel California OSL dating study at 2σ (Arnold *et al.*, 2013).

Between 7 and 11% of quartz grains measured per sample were considered suitable for OSL dating purposes after application of the SAR quality-assurance criteria (Table S2), with the majority of measured grains (63–74%) being rejected from further consideration because they exhibited either weak OSL signals or poor/imprecise dose–response characteristics. All samples contain significant populations of rejected grains with high sensitivity-corrected natural signals that preclude finite and precise D_e interpolation; namely non-intersecting, extrapolated and saturated grain types failing SAR quality-assurance criteria (v) and (vi) (see Supplementary Information). The number of rejected grains falling into these categories amounts to 48–68% of the accepted grain populations for each sample (Table S2), which is consistent with the high proportions of non-intersecting, extrapolated and saturated grains reported for the Hotel California OSL dating samples (42–70%; Arnold *et al.*, 2012a).

While such undesirable grains are routinely rejected during single-grain analysis, they cannot be excluded from multigrain aliquot D_e measurements and are therefore likely to exert significant averaging influences on multigrain D_e datasets. This was confirmed at the neighbouring Hotel California site by Arnold *et al.* (2012a, 2013), who noted that the non-finite D_e values derived from these grain types caused an artificial upward shift in the multigrain D_e datasets relative to the corresponding single-grain D_e distributions. Similar systematic offsets are apparent for the Fuente Mudarra samples when comparing their 'synthetic aliquot' multigrain D_e values (equivalent to multigrain aliquots containing 100 grains;

obtained by summing the signals of all accepted and rejected grain types on each single-grain disc) with the original single-grain D_e datasets (Table S3). The synthetic aliquot D_e values are between 1.2 and 1.9 times higher than the single-grain counterparts for each sample, with the resultant synthetic aliquot ages exhibiting more pronounced scatter and less consistent stratigraphic ordering (Table S3).

The systematic nature of these multigrain averaging effects has potentially important consequences for the reliability of the multigrain OSL burial doses obtained previously by Santamaría *et al.* (2021). We cannot discount the possibility that the existing multigrain D_e datasets inadequately reflect the underlying D_e distributions associated with reliable grain types for these samples. As such, we place greater confidence in the single-grain OSL ages obtained in the present study for ascertaining the chronological relationship of the Fuente Mudarra and Hotel California sites.

The single-grain D_e distributions of grains that passed the SAR quality-assurance criteria are shown as radial plots in Fig. 9a–e. All five OSL samples share broadly similar D_e distributions characterised by moderate dose dispersion (relative D_e range = 1.8–2.7), D_e scatter that is reasonably well-represented by the weighted mean value (as indicated by the significant proportions of grains lying within the 2σ grey bands), and moderate overdispersion of 32 ± 3% to 50 ± 3% (Fig. 9). The overdispersion values for these samples are similar to those reported for most of the single-grain OSL D_e datasets at Hotel California (Arnold *et al.*, 2013), though they are systematically higher than the average overdispersion of 20 ± 1% reported for ideal samples by Arnold and Roberts (2009), as well as the overdispersion values of 15 ± 3% obtained for the single-grain dose recovery test of sample 17188-03. None of the five D_e datasets are considered significantly positively skewed according to the weighted skewness test outlined by Bailey and Arnold (2006) and Arnold and Roberts (2011). Application of the maximum log likelihood (L_{max}) test (Arnold *et al.*, 2009) indicates that the central age model (CAM) is statistically favoured over the three- or four-parameter minimum age models (MAM-3 or MAM-4) of Galbraith *et al.* (1999) for all five D_e datasets.

These various D_e characteristics suggest that additional dose dispersion originating from intrinsic experimental scatter not captured by the dose recovery test (e.g. grain-to-grain variations in luminescence responses due to the fixed SAR conditions; Demuro *et al.*, 2013) and/or extrinsic field-related scatter associated with beta dose spatial heterogeneity (e.g. Nathan *et al.*, 2003; Arnold *et al.*, 2014) have likely exerted a moderate influence on these OSL samples. The D_e datasets do not display the complex signatures commonly reported for heterogeneously bleached single-grain OSL samples, in spite of their colluvial and slopewash origin; i.e. they lack the distinct leading edges of low D_e values and prominent tails of higher D_e values (Olley *et al.*, 1999; Bailey and Arnold, 2006; Arnold *et al.*, 2007, 2011). Any residual doses resulting from potentially limited daylight exposures prior to deposition therefore appear to be relatively minor in comparison with the natural dose ranges under consideration in this study. These observations are consistent with the results of single-grain OSL assessments performed on modern analogue colluvial and slopewash deposits elsewhere in the Sierra de Atapuerca (Arnold *et al.*, 2019).

Localised post-depositional mixing of grains within individual layers (e.g. due to minor bioturbation, chemical–physical alterations or clay shrinking–swelling cycles) could reasonably account for the moderate overdispersion observed for some of the single-grain D_e distributions. However, widespread post-depositional mixing of grains between units is not thought to have contributed significantly to the D_e datasets given the preservation of clear layering and stratigraphic boundaries for Units FM4–FM8.

On the basis of these D_e interpretations, and in accordance with the L_{max} test recommendations noted earlier, we have used the weighted mean (CAM) D_e estimates to calculate the single-grain OSL ages of the five Fuente Mudarra samples (Table 3). The final single-grain OSL ages confirm that Units FM4a–FM8 accumulated over a period of ~35 ka between 84.7 ± 5.9 ka and 119.2 ± 7.6 ka. The archaeological occupation of Fuente Mudarra therefore took place exclusively during MIS 5, with accumulation of the gelifaction-affected uppermost dated units (FM4a–FM5) likely occurring during a colder stage towards the end of the interglacial complex (potentially MIS 5b). These single-grain OSL results confirm that by eliminating the unsuitable grain types identified previously by Arnold *et al.* (2013) at the nearby site of Hotel California it is possible to derive finite ages for all five Fuente Mudarra OSL samples; thereby overcoming the limitations of the initial multigrain OSL dating study at this site (Santamaría *et al.*, 2021).

Discussion

After analysing the archaeological material of Hotel California's different levels, it is apparent that there are similarities in the lithic industry found throughout the sequence in terms of raw materials used, exploitation systems, product characteristics and types of retouch.

Raw materials and technology at Hotel California

Raw materials

Neogene flint is by far the most widely used raw material in every level, which is not surprising given that the occupation was on a secondary deposit of this material. Across the whole area of the Sierra de Atapuerca, this material is not only readily available (Fig. 1a) but of a good quality for knapping, and in formats large enough to exploit easily (Navazo 2006; Navazo *et al.* 2008, García Antón, 2016). For these reasons, Neogene flint always appears as the most used raw material in open-air sites, as well as cave sites in the area (Arsuaga *et al.* 2017; Navazo *et al.* 2011; Navazo *et al.* 2008; Navazo and Carbonell 2014; Santamaría *et al.* 2021). It is usually naturally found without cortex (Navazo *et al.* 2011) because supplies were obtained from secondary deposits, where they could find nB of diverse sizes. Direct procurement of equivalent materials from primary outcrops would have been much harder, given the large size of the surface rocks.

Quartzite supplies were procured from the banks of the nearby rivers (Arlanzón, Pico, and Vena), while Cretaceous flint was easily collected in San Vicente (Fig. 1a), and perhaps some small nodules were also obtained from the riversides, where they were deposited by the current.

The taphonomic processes that commonly affect open-air sites are present at Hotel California, leaving scars on the item surfaces. Neogene flint is the most degraded material because, being the most porous, it is susceptible to saturation, freezing and patinas (García Antón, 2016; Matilla *et al.* 2016). These patinas are varied in colour and are not present in artefacts made from other materials. It is quite possible that illuviation and seasonal water saturation are responsible for them (Santamaría *et al.* 2021). Items from Hotel California display gelifraction domes and scars, having been exposed to cold weather conditions for prolonged periods of time.

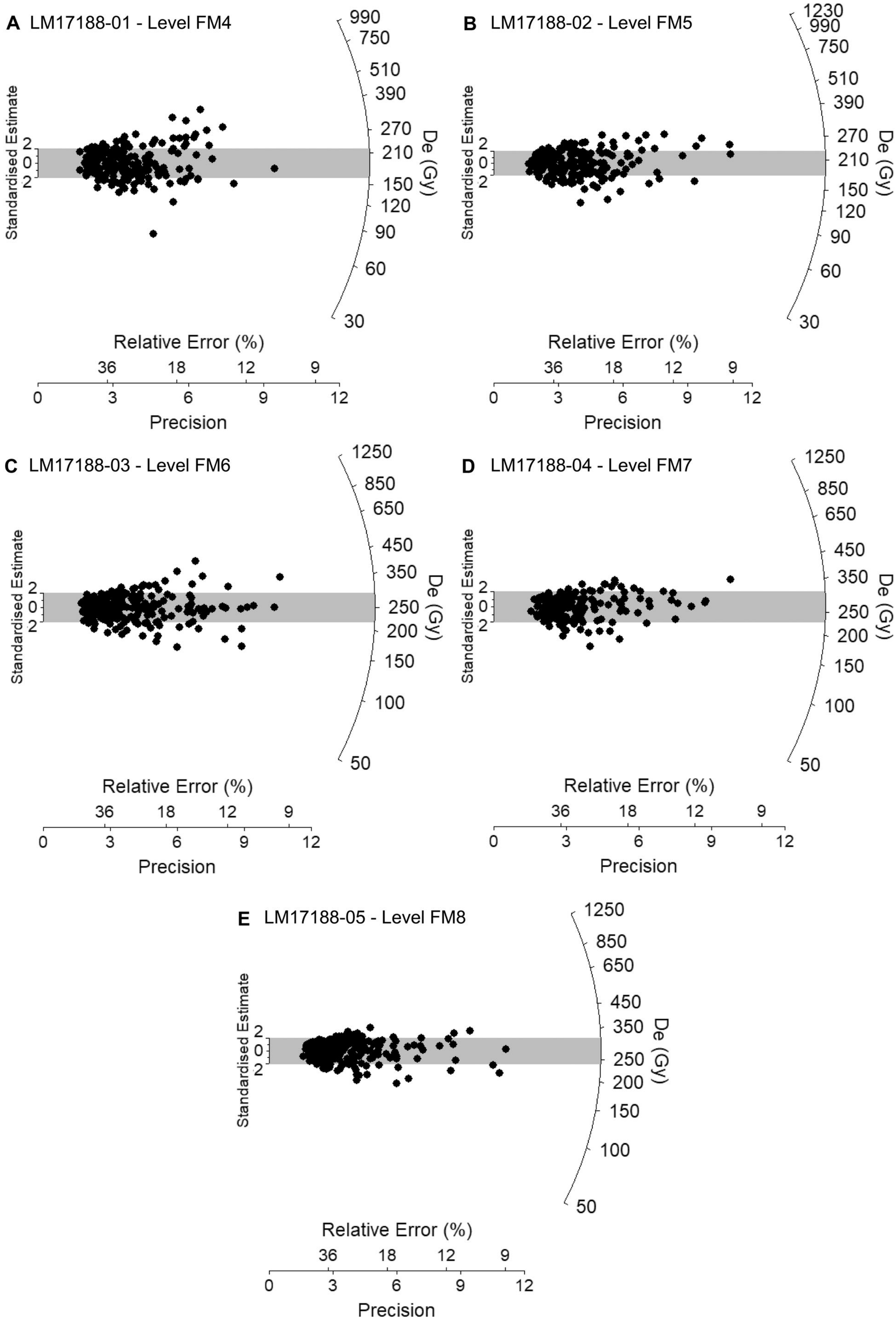

Figure 9. Single-grain OSL D_e distributions for the Fuente Mudarra OSL samples dated in this study, shown as radial plots. The grey bands are centred on the D_e values used for the age calculations, which were derived using the central age model (CAM) of Galbraith *et al.* (1999).

The procurement of raw materials evidenced at Hotel California is similar to that at other Mousterian sties in the Sierra de Atapuerca, namely Fuente Mudarra, Hundidero and Galería de las Estatuas. Having established a more secure chronological framework for Fuente Mudarra using the same single-grain OSL dating approach employed previously at Hotel California and Galería de las Estatuas, we are now able to better ascertain the temporal and technological relationships of these various Mousterian sites.

As noted earlier, the open-air site of Fuente Mudarra is located close to Hotel California (~200 m away), with both sites found on the same margin of the Pico River and at similar elevations along a slope that preserves Pleistocene deposits. The single-grain OSL dating results from the current study confirm that the six archaeological levels at Fuente Mudarra span 119.2 ± 7.6 ka (FM8) to 84.7 ± 5.9 ka (FM4). Despite its earlier occupation age, the lithic assemblages recovered from this site are very similar (Santamaría *et al.* 2021) to those described for Hotel California, particularly regarding the use of raw materials. The Neogene flint used was also local and derived from secondary deposits, and the largest rocks found at the site measured 220 mm. The provisioning sources used by the groups that occupied Hotel California were also used by the preceding groups that occupied Fuente Mudarra, where 90% of items in every level were of Neogene flint and less than 10% were of Cretaceous flint. The Neogene flint artefacts in Fuente Mudarra have patinas like those in Hotel California, with the same coloration as well as the same gelifraction scars, which suggests that both sites were exposed to the same post-depositional processes.

Hundidero, another open-air site dated to between 70.6 ± 11 ka and 58.8 ± 4.9 ka using thermoluminescence (Navazo *et al.* 2011), has similarities with Hotel California and Fuente Mudarra in terms of raw materials. Its registers show that the groups occupying this site also procured local Neogene flint, selecting blocks that had lost their cortex from the secondary deposits that were close to the site (Navazo *et al.* 2011).

Galería de las Estatuas is a cave site in the uppermost level of the Cueva Mayor–Cueva del Silo karst system, which has single-grain OSL chronologies that span 112 ± 7 ka to 70 ± 5 ka (Demuro *et al.* 2019a). The Mousterian occupation of this site therefore coincides with that of Fuente Mudarra Units FM4–FM8 (119.2 ± 7.6 ka to 84.7 ± 5.9 ka), and partially overlaps with the initial occupation phases of Hundidero (Unit 4; 70.6 ± 11 ka) and Hotel California (Unit I/Level 7; 71.0 ± 5.6 ka). Examined in two test pits, Galería de las Estatuas' four stratigraphic units reveal a clearly Mousterian industry. Items at Galería de las Estatuas are 83.8% flint, and all of the raw materials used are of local origin. Operative chains appear fragmented, and the early stages of exploitation are not represented in the lithic assemblage (Arsuaga *et al.* 2017), which means that the first phases of exploitation were carried out outside the cave.

Exploitation systems

The exploitation systems that we see through the whole sequence at Hotel California are very similar: tests were done quite simply, with unipolar and orthogonal longitudinal removals, and exploitations were often begun as orthogonal bipolar. Indeed, these first orthogonal exploitations were often carried out bifacially, perhaps with the purpose of preparing the planes until they were adequately transformed into a centripetal bifacial system, which was for the most part non-hierarchical. For other items, in which the nB's angles were already apt, exploitation was then unifacial centripetal, as can be seen in Level 7 especially.

In general, reduction methods were meant to exploit the base's larger surfaces and work secant planes with a tendency to centripetal directions. Discoidal or centripetal secant plane methods are very efficient for producing flakes. The base's initial volume is reduced without wasting too much material and without much need for reconditioning (Vaquero *et al.* 2012). Moreover, nonhierarchical exploitation increases the core's productivity (Vaquero and Carbonell 2003).

Exploitation products help confirm that cores were worked similarly in the entire assemblage. The complete PBs found show traces of having been derived from centripetal and chordal exploitations. Types associated with centripetal (A1) and chordal (A2) exploitation systems of secant planes represent 97% of the identified PBs ($n = 91$), while those of type B, which come from centripetal exploitation of parallel planes, are only represented by three PBs. We also identified a Kombewa flake of Cretaceous flint in Level7. The object of these exploitations is the production of flakes for their direct use, with few demands on their shape and size.

Exploitation strategies in Fuente Mudarra were the same as at Hotel California. Through the entire sequence, cores were exploited using bifacial centripetal systems of secant planes. Very little variation characterises the centripetal or discoidal schemes in Fuente Mudarra: there are no clear hierarchical cores and most cores tend to be symmetrical. Sporadically, we see systems like bipolar opposite. A core that reached advanced exploitation phases was recycled as retouched tools, and another was changed from a bifacial to a trifacial system. No exhausted cores were found. This was also true for Hotel California. The analysis of Fuente Mudarra's exploitation products concluded that 59 PB were of type A, derived from centripetal exploitation methods of secant planes, and seven PB were of type B, produced by centripetal exploitation methods of parallel planes (Santamaría *et al.* 2021).

The exploitation systems identified in Hundidero's four levels are based on discoid schemes, with the sporadic presence of techniques such as Levallois, Kombewa and, in some cases, unipolar longitudinal, orthogonal and multipolar. There are no fully exploited cores, and some are in the early stages of exploitation. The analysis of previous removals on their dorsal faces reveals that many PBs were derived from centripetal systems (Navazo *et al.* 2011).

Things are somewhat different in Galería de las Estatuas when compared with these open-air sites: there are exhausted cores in the cave site. Core exhaustion makes it difficult to identify the exploitation system, but those identified include centripetal, Levallois and bipolar on anvil, as well as a Kombewa flake (Arsuaga *et al.* 2017).

Configuration

The number of retouched tools is very low in all the Hotel California levels (around 4%), which means that retouching was clearly not the main purpose of the knapping. Among the most representative tools found are sidescrapers, denticulates, notches, points, becs, endscrapers and abrupts. Three items that exhibit a double patina on their retouches (Level5, Level6 and Level7) were recycled, and there were several other retouches on fragments of Neogene flint in Levels 3, 5 and 6.

In Fuente Mudarra, at less than 3%, retouches are scarce in every level. At this site, knapping was not used to configure tools either but to obtain flakes to use as natural cutting edges. Four of the PB found in Fuente Mudarra were included in the use-wear study of Santamaría Cabornero *et al.* (2021), which concluded that one of them was used for scraping hide, two were used for wood scraping and one was used on soft or semi-soft material. There were also tools configured on discarded fragments and some with a double patina. This dynamic is similar at both sites. The most abundant types in Fuente Mudarra are sidescrapers and denticulates, followed by notches, bec, abrupts, endscrapers and Tayac points in Levels 4 and 8 (Santamaría *et al.* 2021).

The kinds of retouch present in Hundidero are notches, denticulates, sidescrapers, endscrapers, points and becs. Double patinas in retouches have also been documented. What makes Hundidero different from Hotel California and Fuente Mudarra is a tendency towards microlithism. The reason might be the type of occupation, for Hundidero was apparently used on occasional visits for very specific tasks (Navazo *et al.* 2011).

In Galería de las Estatuas, retouches such as sidescrapers (one Quina), denticulates, points, endscrapers and abrupts represent 8% of the lithic assemblage. The first stages of the operative chain were probably performed outside, while inside the cave, where many microflakes and knapping debris were found, knappers carried out intense retouching activities before taking the tools outside to use and then abandon once they were no longer wanted. This was assumed from the fact that few tools were found inside. A microlithism similar to Hundidero is also present at Galería de las Estatuas (Arsuaga *et al.* 2017). The cave was occupied by Neanderthal groups to consume red deer, equids and bovids, and it was also occupied sporadically by carnivores. In sum, the MIS 5 to MIS 3 Mousterian sites of the Sierra de Atapuerca share a technology that we can summarise as based on: (i) local sourcing, principally of Neogene flint, which is readily available in the area; (ii) exploitations following discoidal systems, which occasionally incorporate others (in the early stages, unipolar, bipolar and orthogonal) and, sporadically, Levallois and Kombewa; (iii) knapping that is geared towards obtaining flakes for immediate use and a small percentage of retouched items, which produces similar types at all of the sites. These technological trends are also documented in the unstratified surface remains found extensively across the area (Navazo and Carbonell 2014). These sites were recurrently visited, as can be seen by the presence of double patinas and various levels of occupation at each site.

Mousterian technology at the surrounding sites

There are various cave sites in the surrounding environs of the Sierra de Atapuerca that preserve evidence of Mousterian occupation, including Cueva Millán, La Ermita, Valdegoba, Prado Vargas, Peña Miel and Abrigo del Molino (Fig. 1b).

Cueva Millán, whose Levels 1a and 1b have been radiocarbon (^{14}C) dated to 37.4 ± 0.6 and 37.6 ± 0.7 ^{14}C kyr BP (equivalent to a combined 95.4% calibrated age range of 42.7–41.2 cal. kyr BP) (Moure Romanillo and Garcia-Soto, 1983), has three levels of Mousterian lithic industry (Moure Romanillo and García-Soto 1983b). The superficial Level 1a is dominated by discoidal exploitations with the presence of Quina and prismatic cores for the production of flakes (Navazo 2010); sidescrapers with a significant percentage of Quina retouches; and notches, denticulates and a high proportion of blades and elements of the Upper Palaeolithic. Regarding the remaining levels, Moure Romanillo and Garcia-Soto (1983) describe the few pieces found in Level 1b as an assemblage characterised by the presence of convex and transversal sidescrapers, notches and denticulates; the absence of Levallois; and a scarce representation of Upper Palaeolithic items. In Level 1c, only 20 tools are described, mostly sidescrapers, notches, endscrapers and denticulates.

In the nearby site of La Ermita, the latest U-series dating study (Sánchez Yustos and Diez Martín 2015) revealed capping speleothem ages of 101.8 ± 4.0 ka for Level 5a and 95.1 ± 5.7 ka for Level 5b. Amino acid racemisation dating of two teeth from Level 5a has also yielded consistent ages of 128.8 ± 39.2 ka and 114.3 ± 41.9 ka (Díez *et al.*, 2008), suggesting that the Mousterian levels formed during MIS 5. In both Levels 5a and 5b, the use of flint and discoidal exploitation predominates, both bifacial and unifacial. Although the technology in both levels is similar, the lithic industry of Level 5a seems slightly more elaborate than that of Level 5b, and is closer to that of the superficial level of Cueva Millán (Navazo 2010).

In Valdegoba, Unit D has been ^{14}C dated to 48.4 ± 3.3 ^{14}C kyr BP (equivalent to an infinite 95.4% calibrated age of >46.9 cal. kyr BP) (Dalén *et al.*, 2012), while the capping speleothem for Unit 7 has been U-series dated to $<73.2 \pm 5.0$ ka (Quam *et al.*, 2001). The lithic industry found in Unit D's two levels shows little technological variation (Díez *et al.* 2014). The predominant exploitation systems are discoidal and recurrent Levallois, and there is a nearly equal proportion of flint and quartzite items, but the exploited cores are mostly flint. Although there are no blade cores, there are 75 products of laminar tendency (Terradillos-Bernal, Díez Fernández-Lomana, 2018). The tools are not large, and the most frequent are sidescrapers, followed by denticulates, notches, points and composite tools such as denticulate-scrapers. They show few signs of resharpening, and are associated with domestic tasks.

At Prado Vargas Cave there is evidence of occupation in several levels. The chronology of N4 has been constrained to between 54.7 and 39.8 ka using a combination of single-grain OSL and ^{14}C dating (Navazo Ruiz *et al.*, 2021). At 91.9%, the most predominant raw material is local flint, and it is exploited mostly in discoidal schemes that are often hierarchical. These exploitations generate products that are morphologically close to Levallois and laminar. There is evidence of recycling, with fractured cores being re-exploited and exhausted cores recycled as tools (Navazo *et al.* 2022), while bone fragments were used as retouchers (Alonso-García *et al.* 2020).

Peña Miel, on the upper stretch of the Ebro River, has three levels with archaeological remains from the Middle Palaeolithic. Two of them have been ^{14}C dated: Level g at 45.0 ± 1.3 ^{14}C kyr BP (equivalent to a 95.4% calibrated age range of 51.6–45.1 cal. kyr BP), and Level e at >40 ^{14}C kyr BP and 39.9 ± 10.5 ^{14}C kyr BP (equivalent to an infinite combined 95.4% calibrated age range of >36.3 cal. kyr BP) (Utrilla and Montes, 1993; Montes et al. 2001). Quartzite is the predominant material in Level e, and it is exploited with chordal discoidal systems to produce pseudo-Levallois points and sidescrapers with scalar retouches. The flint used is allochthonous, most of it gathered 20–30 km away, with some procured as far as 60 km away. Flint cores were worked using Levallois systems to produce semi-Quina sidescrapers, very few denticulates, and no notches (Rios-Garaizar and Eixea 2019). Exploitation is adapted to the raw material, and there is evidence of ramification in the exploited flint. Level g produced more lithic and faunal remains and bone retouchers. Quartzite was worked similarly to that found in Level e, and the presence of more exhausted cores reveals that flint was exploited more intensely. These differences, added to the changes in environmental conditions, reveal that what is now Level g was more intensely or recurrently occupied, thanks to more favourable weather conditions, whereas the harsher conditions experienced at Level e allowed for a more occasional, perhaps seasonal, occupation (Rios-Garaizar and Eixea 2021).

Abrigo del Molino has, so far, three levels of Mousterian occupation, which have been dated using a combination of ^{14}C and K-feldspar post-infrared infrared stimulated luminescence (pIR-IRSL): Level 2 (combined 95.4% calibrated age range of 45.4–42.5 cal. kyr BP), Level 3 (combined 95.4% calibrated age range of 44.6–41.2 ka; pIR-IRSL age = 42.4 ± 2.7 ka) and Unit k (bracketing pIR-IRSL ages of 42.4 ± 2.7 and 44.8 ± 3.3 ka) (Kehl *et al.* 2018). The lithic assemblages of Levels 2 and 3 are very similar, and most of the raw materials used are of local provisioning, except for the flint, whose origin is unknown. Exploitation systems were discoidal and Levallois, with a higher proportion of Levallois in Level 3. The most represented products are denticulates, notches and choppers. There is a large proportion of flakes under 2 cm in size in both levels, although they are more abundant in Level 2. Occupation of this cave has been interpreted as representing ephemeral visits (Álvarez-Alonso *et al.* 2018).

There are commonalities between these MIS 5–MIS 3 cave sites and the MIS 5–MIS 3 open-air sites of Atapuerca, such as the local raw material procurement, a preference for discoidal systems, the production of small flakes, and the predominant types of retouched items. Equally, there are many more differences between the various localities. At some cave sites, not all of the raw material is autochthonous; there are diversified exploitation systems with hierarchical schemes; operative chains are fragmented with organised recycling and a ramification of operations; tools are resharpened or recycled; and laminar technology is present.

Technology can vary more significantly from one level to the next at some of the sites around this area that have multiple excavated levels, such as Millán Cave (three levels), La Ermita (two levels) and Peña Miel (two levels). Each level displays slight differences in occupation, which in the case of Hotel California is limited to small variations in the percentages of the raw materials used.

The answer to these questions could lie in factors already identified by other authors, such as technological (Kuhn 1993), chronological (Mellars 1996), climatic and mobility (Rolland 1981), or the classic ones based on the function of each site (Binford, 1973), or the cultural tradition of the different groups (Bordes, 1961b), as well as a combination of various of them (Rolland and Dibble 1990; Delagnes and Meignen 2006; Delagnes, Jaubert and Meignen 2007; Jaubert 2011; Delagnes and Rendu 2011; Moncel and Daujeard 2012; Monnier and Missal 2014; among others) which has kept the Mousterian debate alive until the present.

In our case study, the Sierra de Atapuerca, the recurrence of occupations over perhaps several generations and with a significant technological tradition, means that no substantial technological changes are noticeable. However, it should be noted that at other contemporary sites on the northern plateau (already mentioned above) there may have been occupations that are either not repeated or not carried out by the same groups. This means that there are detectable technological changes in the archaeological record.

All of this leads us to propose, as a working hypothesis, the technological tradition of the groups in this area. But among the lines of work to be contrasted, we must take into consideration others such as: (i) the accuracy of the dating is insufficient to be able to see the succession or evolution of these different technologies within this region; (ii) adaptation of different technological strategies in response to climatic or environmental changes; (iii) different settlement patterns according to the location of the sites; (iv) variations in the function of the settlement, as well as the duration of the occupations (short/long term) that produce different technological responses; and (v) population shifts that leave the remains of different groups.

Low-cost technologies

The lithic assemblages uncovered in the different levels of Hotel California reveal a technology that could be defined as low cost. Admittedly, the costs of procuring raw materials, the costs of exploiting and producing bases, and the costs of manufacturing tools all entailed a moderate investment of time and effort. However, Vaquero and Romagnoli (2018) consider expedient technologies to be characterised by low-cost strategies, which entail: (i) the almost exclusive use of local raw materials; (ii) sequences of reduction oriented towards flake production, with a low level of predetermination; and (iii) low percentages of retouched artefacts. All of these characterise the archaeological sites of Hotel California and Fuente Mudarra, where low-cost strategies are present in the local provisioning; the election of natural bases (i.e. selection of manageable sizes and naturally removed cortex); the use of relatively simple exploitation methods, predominantly centripetal and orthogonal, with a low presence of hierarchical elements and the total absence of exhausted cores; the production of PB for use of their natural cutting edges; and a very small proportion of retouched tools.

The word 'expedient' has connotations that suggest such technologies are poorer than those referred to as 'curated'. This could be a mistaken interpretation, for low-cost technologies are equally functional and adapted to their purposes, while providing simpler and quicker solutions. They are not used because the groups lack the same technical knowledge as other groups that use high-cost strategies, but because, for different reasons, the fabrication of their tools at a particular site can be resolved at a low cost.

Many hypotheses try to explain these behaviours. One such hypothesis argues that differences in technological organisation are related to group settlement patterns, with curated technologies associated with high mobility (tools appropriate for trips for different purposes, distances and durations), while expedient technologies are associated with sedentary patterns (Binford 1977, 1979). Low mobility and stable or highly recurrent occupation itself is associated with expedient technology and spaces where adequate raw material is abundant and readily available, making it possible for the group to predict what they will need in that specific space throughout a given period (Kelly 1988; Parry and Kelly 1987; Nelson 1991).

However, the very opposite idea has also been hypothesised: that diversification of technology and proliferation of specialised tools associated with curated technologies takes place in low-mobility contexts, whereas more mobile groups adopt tools that are more versatile in their uses, given the great cost that transporting task-specific tools would entail (Bousman 1993).

Other hypotheses point to the availability of raw materials. Scarcity, whether because of the geological context or limitations determined by the settlement pattern, encourages the development and use of a curated technology that implies a greater investment in time and effort to make more efficient use of the available supplies, as well as the significant presence of recycling. In the context of abundant raw materials, the maintenance and recycling of tools is more costly than discarding them and making new ones (Bamforth 1986).

The factors that condition these behaviours have also been attributed to the availability and predictability of resources necessary for subsistence beyond lithic procurement (Bleed 1986). The organisation of technology can be informed by different hunting strategies, so that complex tools can be interpreted as a technological optimisation for hunting ephemeral or seasonal prey, and expedient technologies in the context of less demanding hunts.

An alternative hypothesis suggests that these differences in technology were informed by the practice of various activities and the amount of time dedicated to the manufacture of the necessary tools. The overlap between activities resulted in a curated production to prevent this time stress (Torrence 1983). When the frequency of a given task increased, a greater tool specialisation resulted (Hayden and Gargett 1988). This gave rise to a curated technology, with lithic products differentiated by activity, and changes in the use of raw materials and forms of recycling. Changes in processing requisites determine the type of technological strategy used (Tomka 2001).

Another explanation suggests that high-cost technologies are related to the symbolic information that a given group's knappers managed as cultural markers. Changes such as demographic increases could have led to the interaction of different groups that adopted or added these expressions of social identity, which were reflected in their manufacture of tools (Moore 2013).

At Hotel California, a context with abundant raw materials, we find occasional examples of recycling, evidenced by the double patinas that are visible in the retouches of some tools and the reuse of fragments. Although recycling is usually associated with high-cost technologies that increase a tool's life (Vaquero 2011), the type of recycling found at Hotel California seems to respond to immediate needs and is quite sporadic. This type of behaviour can occur in low-cost contexts in which there is little preoccupation with the characteristics of the product that is obtained (Vaquero and Romagnoli 2018). The chosen bases do not stand out for their shape or ergonomics. Large, thick flakes and core flanks with recycling in the form of double patinas reveal that these open-air sites on the banks of the Pico River were repeatedly occupied over tens of thousands of years.

The recurrence of this type of technology during lengthy and distinctive time periods, namely between ~71 and ~48 ka in the case of Hotel California, and ~119 to ~85 ka in Fuente Mudarra, is significant. Such recurrence is less marked in the other regional MIS 5–MIS 3 sites discussed above (Cueva Millán, La Ermita, Valdegoba, Prado Vargas, Peña Miel and Abrigo del Molino), for these have shorter sequences and temporal durations spanning 6–15 ka (as dated so far). In contrast, the Atapuerca Mousterian sequences consistently span longer durations: Hotel California, ~24 ka; Fuente Mudarra, ~35 ka; Hundidero, ~12 ka; and Galería de las Estatuas, ~42 ka.

To find sequences similar to the Atapuerca Mousterian sites in terms of chronological duration, it is necessary to consider sites further away from the Iberian Peninsula such as Esquilleu, El Castillo or Axlor, in the Cantabrian range (Baena *et al.* 2021; Martín-Perea *et al.* 2022; Rios-Garaizar 2017); Teixoneres, Abric Romani, Cova Negra, el Salt, Abric del Pastor and Abrigo de la Quebrada, near the Mediterranean coast (Zilio *et al.* 2021; Sharp *et al.*, 2016; Chacón *et al.* 2013; Gómez de Soler *et al.* 2019, 2020; Romagnoli *et al.* 2016; Vaquero 1999; Eixea *et al.* 2020; Galván *et al.*, 2014; Machado *et al.* 2013; Machado *et al.* 2019; Mallol *et al.* 2019; Real *et al.* 2020); or Carihuela, Bajondillo and Gorhams Cave in the south of the Iberian Peninsula (Carrión *et al.* 2019; Cortés-Sánchez *et al.*, 2019; Barton and Jennings 2013; Higham *et al.* 2013; Rhodes 2013) but we do not find examples like these within the geological limits of the northern plateau.

Among the aforementioned sites we mostly find technological variation of different knapping strategies and management, with either abrupt or gradual changes (as seen at sites where a detailed lithic study has been carried out) (e.g. Rios-Garaizar 2017). While those with stable sequences in their lithic management, such as the case of Gorhams Cave, more similar to the assemblages presented in the open air at Atapuerca, are also interpreted as sites with a land-use strategy consisting of localised and relatively low levels of residential mobility (Barton and Jennings 2013). Likewise, outside this area of the northern plateau, multiple open-air sites show a wide variety of occupation types, from ephemeral workshops to encampments, but most frequently short-term occupations (Eixea *et al.* 2022).

Conclusions

The Hotel California open-air site has a sequence of Mousterian levels that stands out because of the relative homogeneity of its technology, which could be described as low cost. The Neanderthal groups that lived in the Sierra de Atapuerca knapped tools mostly from Neogene flint, the provisioning of which was carried out at the site itself. Knapping strategies were predominantly centripetal, with the object of producing flakes from cores that received little reconditioning on their knapping planes. Flakes were small and were used directly, and there is a very low percentage of retouched tools. The configuration of sidescrapers, denticulates and notches is prominent.

The similarities between Hotel California and Fuente Mudarra are striking, in spite of spanning non-overlapping time ranges during MIS 5–MIS 3. Both belong to a large extension above the Pico River from where the valley can be controlled, and are part of a territory repeatedly exploited by Neanderthal groups over tens of thousands of years. Indeed, it is feasible that the entire territory between the River Arlanzón and River Vena (Fig. 1a) could be considered as a single locality characterised by concentrations and dispersions of archaeological remains, which collectively provide insights into the management of the landscape and daily lives of local Neanderthal groups.

The consistency of Hotel California's entire lithic sequence, as well as that at the nearby site of Fuente Mudarra can be attributed to a settlement of Neanderthal groups that repeatedly occupied the environs of the Sierra de Atapuerca. This strategic ecological environment, where the resources of vegetable and animal biomass were abundant, and the necessary conditions for the development of hunting and gathering were present, enabled the groups to recurrently exploit this area. Within this territory, the groups returned again and again to Hotel California and Fuente Mudarra over a combined period spanning ~119–48 ka to carry out common tasks such as knapping and other activities (like working on wood and hides in the case of Fuente Mudarra) (Santamaría Cabornero *et al.* 2021).

The expedient technology evident in Hotel California could be related to: (1) a settlement pattern of low mobility and high recurrence, as suggested by the chronological evidence for combined occupation of these Mousterian sites over a duration of 70 kys; as well as (2) the abundance and availability of raw materials, as seen in the multiple outcrops and secondary deposits in the area.

The wealth of this area – its strategic situation, the presence of habitable caves, the ready availability and abundance of raw materials, water, and food sources (Carbonell *et al.* 2014; Rodríguez *et al.* 2011; Arsuaga *et al.*, 2017) – might be the key that explains the choice of both an expedient or low-cost technology, as well as the recurrence of occupation during MIS 3–MIS 5, for all of the resources necessary for the life of hunter-gatherer groups were found here.

Declarations

Competing interests: The authors did not receive support from any organisation for the submitted work. The authors have no competing interests to declare that are relevant to the content of this article.

Acknowledgements. This work was funded by the Spanish Ministry projects CGL2012-38434-C03-02, CGL2015-65387-C3-3-P and PGC2018-093925-B-C31. The field excavation work was funded by the Junta de Castilla y León and Fundación Atapuerca. Marta Santamaría has a predoctoral fellowship from the University of Burgos. Martina Demuro is supported by Australian Research Council Future Fellowship grant FT200100816. The excavation team has made this research possible. We would like to give special thanks to Hector de la Fuente and Pedro Alonso, colleagues of the Prehistory Laboratory of the UBU, for their constant support.

Data availability statement

Research data are not shared.

Supporting information

Additional supporting information can be found in the online version of this article.

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