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RESEARCH ARTICLE

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Patterns of lithic procurement strategies in the Pre-Pyrenean Middle Magdalenian sequence of Cova del Parco (Alòs de Balaguer, Spain)

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Abstract

Archaeological studies carried out in recent decades have demonstrated that the Pre-Pyrenees, a mountain range in north-east Iberia, were regularly frequented by several human groups during the Late Pleistocene. The Cova del Parco archaeological site is an example of this large-scale and regular human presence. The site was discovered and first excavated in the 1970s, and since the 1980s, a team from the University of Barcelona has been conducting archaeological work. So far, we have found that the site was at least frequented from the Middle Magdalenian upon historical times. In this paper, we present the results of the archaeopetrological, geochemical and geographic information system (GIS) analyses of chert tools ascribed to the Middle Magdalenian sequence. The textural, micropalaeontological and geochemical analysis of the lithic artefacts has allowed us to identify several chert types from local, regional and long-distance sources. Some of these cherts had their origin in the northern slopes of the Pyrenean chain, suggesting that this mountain chain was regularly crossed by Magdalenian groups. Next, we performed GIS analyses to determine the paths and connections that may have linked the archaeological site with the different chert outcrops, and to identify the best routes for crossing the Pyrenean Mountain range. Moreover, this study provides a larger vision of the mobility and the complex economic interactions between the different Magdalenian groups that settled Cova del Parco at the end of the Late Pleistocene.

KEYWORDS

chert, geochemistry, GIS, human mobility, Pyrenees, Upper Palaeolithic

1 | INTRODUCTION

The geochemical analysis of chert tools recovered at Palaeolithic sequences has been proven to be a useful approach for inferring past human mobility and lithic procurement strategies. The traditional approach, mostly focusing on macroscopic and petrographic characterizations, is limited in the case of a convergence of facies, that is, where different geological formations possess very similar features (Aubry, 1990). In contrast, geochemical analysis usually allows the identification of differences between sources and, thus, helps to pinpoint the origin of the archaeological remains (e.g., Brandl & Hauzenberger, 2018; Golovanova et al., 2021; Stewart et al., 2020). Several analytical techniques have been applied in Western Europe to characterize the lithic artefacts recovered at Palaeolithic sequences, quantification of the trace elements and rare earth being the most frequently used as the key to solve the problem at hand (e.g., Eixea et al., 2021; Muntoni et al., 2022; Pereira et al., 2021). In our study, we used two analytical techniques that are already well known and well tested in chert samples, energy-dispersive X-ray fluorescence (ED-XRF) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), as they work in a complementary and nondestructive way to define the major, minor and trace elements of chert samples (Sánchez de la Torre et al., 2017a, 2019a, 2023).

This paper focuses on the Pyrenean Mountain Range, a key area for the study of the relation between Upper Palaeolithic hunter-gatherer communities and mountain environments and for establishing whether the territory covered by these groups incorporated both slopes of the Pyrenean Mountain range. Archaeological research has demonstrated that contacts between the two sides of the Pyrenees existed during the Upper Palaeolithic, as evidenced by the similarities between the symbolic expressions (Garate et al., 2015), the lithic techno-typological analyses (Calvo, 2019; Langlais et al., 2016) and the lithic raw material procurement (Calvo & Arrizabalaga, 2021; Sánchez de la Torre et al., 2023) on the two slopes. Thus, through the geochemical approach and a geographic information (GIS) analysis of chert artefacts, we aim to identify the origin of the chert lithic assemblage recovered at the Middle Magdalenian archaeological level from Cova del Parco in order to provide new data regarding the mobility and the territoriality of these hunter-gatherer societies. As other recent and similar—in terms of chronology—studies of archaeological sets in NE Iberia indicate (Arrizabalaga et al., 2014; Calvo & Arrizabalaga, 2021; Sánchez de la Torre et al., 2019c, 2020, 2023), Upper Palaeolithic societies possessed larger territories of exploitation than traditionally supposed, at least with regard to lithic resources. This large mobility of lithic resources in NE Iberia often involved both slopes of the Pyrenean chain. For this reason and considering the data obtained from the archaeological site of Cova del Parco, we reckon that it is a priority to add GIS analysis in order to define the probable routes that past societies may have taken to procure lithic raw materials.

2 | COVA DEL PARCO ARCHAEOLOGICAL SITE

Cova del Parco is located in the mountainous foothills of the Pre-Pyrenees, in the municipality of Alòs de Balaguer, La Noguera, in the province of Lleida. The site is located at 420 m asl and 120 m above the current course of the river Segre, one of the routes that cross the Eastern Pyrenean Mountain Range, finally flowing into the river Ebro. The site, which faces south, has a single triangular gallery about 10.5 m long per 4.5 m wide at the entrance. The cave is connected to a large shelter just over 5 m long per 30 m wide, enclosed by a masonry wall made in recent periods (Figure 1).

The site was discovered in the 1970s, but the first interventions were carried out by Professor Joan Maluquer de Motes, who led excavation seasons in 1974, 1975 and 1981. These first campaigns involved the almost complete emptying of the upper levels of the stratigraphy, which contained the ceramic levels. In 1984, Prof. Maluquer de Motes made a 3 m^2 trench excavation in the central part of the gallery, which allowed him to establish a stratigraphic sequence in six strata, in the deepest of which he located a group of lithic materials from the end of the Upper Palaeolithic (Maluquer de Motes, 1984). In 1987, the Research Seminar of Prehistoric Studies (SERP) from the University of Barcelona, under the supervision of Dr. Josep Maria Fullola, started the excavation of the Upper Palaeolithic levels. The site has been continuously excavated since then by researchers from the SERP research group, under the leadership of Dr. Xavier Mangado, Dr. Marta Sánchez de la Torre and Dr. Cynthia B. González.

The archaeological materials recovered during Prof. Maluquer's interventions show diverse Neolithic occupations from the Early Neolithic (Cardial ware) to the Early Bronze Age. The work carried out by the SERP has made it possible to document a cultural sequence that presents three major horizons. First, in the remains of the Neolithic levels, mostly emptied by Dr. Maluquer's interventions, the basal part of a storage structure radiocarbon dated from charcoal remains at 7250–6750 cal B.P. was documented, dating the ceramic content of its abandonment during the Early Neolithic (Epicardial ware), when it was reused as a dump (Petit, 1996).

The systematic excavations carried out from 1987 onwards recorded an Epipaleolithic occupational sequence, excavated between 1993 and 1999, with the classic Epipaleolithic sequence in the Iberian Mediterranean coast defined by Fortea (1973). Below a very old Iberian geometric Epipaleolithic horizon (level Ia2, at depths of −175/−200 cm), dated to 13,000–12,500 cal B.P. with microburin technique and geometric industry of Sauveterrian type (triangles and segments), an Iberian microlaminar Epipaleolithic phase appeared (levels Ib and Ic, at a depth of −175/−200 cm).

Below the Iberian microlaminar horizon, and after an episode of abandonment, a significant Magdalenian sequence, still under excavation, was recorded. At an elevation of −230/−240 cm, a Late Upper Magdalenian thin horizon (radiocarbon dated to 15,000–14,200 cal B.P.) was documented. This level was

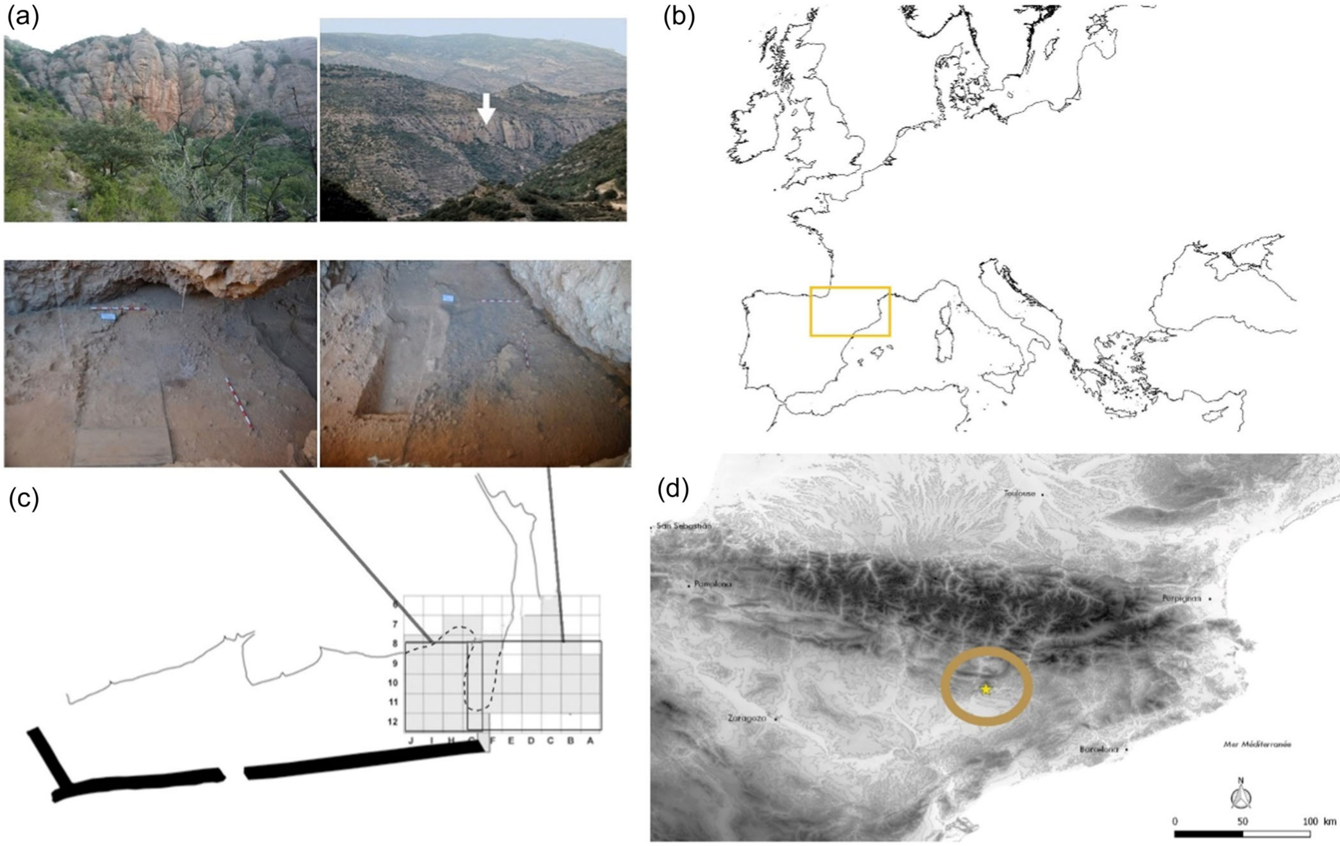

FIGURE 1 Location of Cova del Parco. (a) Detail of the surrounding landscape and excavation area. (b) Location of the studied area in the European context. (c) Detail of Parco's excavation plan. (d) Geographical context of Cova del Parco in the NE Iberian Peninsula.

TABLE 1 Radiocarbon dates obtained from charcoal samples recovered at Cova del Parco since 1987 and calibrated with OxCal Online Program v. 4.4 with the IntCal20 Northern Hemisphere Radiocarbon Age Calibration Curve (Reimer et al., 2020).

Reference	Nature	Level	Area	Date B.P.	Date cal B.P.
GrN-20058	Charcoal	Silo	Silo	6120 ± 90	7250–6750
GifA-95562	Charcoal	Ia2	Hearth	10,930 ± 100	13,073–12,740
GifA-95563	Charcoal	Ia2	Hearth	10,770 ± 110	12,989–12,594
OxA-8656	Charcoal	Ib	Hearth	11,430 ± 60	13,400–13,200
OxA-10796	Charcoal	II	Hearth	12,605 ± 60	15,224–14,575
OxA-10797	Charcoal	II	Hearth	12,460 ± 60	14,981–14,296
OxA-10835	Charcoal	II	Hearth	12,560 ± 130	15,282–14,237
OxA-13597	Charcoal	II	Hearth	12,995 ± 50	15,731–15,336
OxA-13596	Charcoal	II	Hearth	13,025 ± 50	15,775–15,377
OxA-17730	Charcoal	II	Hearth	13,095 ± 55	15,899–15,511
OxA-29336	Charcoal	III	Hearth	13,255 ± 50	16,096–15,739
OxA-23650	Charcoal	III	Hearth	13,475 ± 50	16,405–16,043
CNA-5700-1-1	Charcoal	III	Hearth	13,451 ± 64	16,410–15,987

separated from the rest of the Magdalenian sequence by a block fall (−240/−260 cm). Below, the Upper Magdalenian sequence develops (level II, elevation −285/−320 cm), radiocarbon dated to 15,900–15,300 cal B.P. and characterized by the presence of elongated scalene triangles (Mangado et al., 2014). Below, a Middle Magdalenian occupation has been identified (level III, starting at −320 cm), radiocarbon dated to 16,400–16,000 cal B.P. and still under excavation (Mangado et al., 2018) (Table 1, Figure 2).

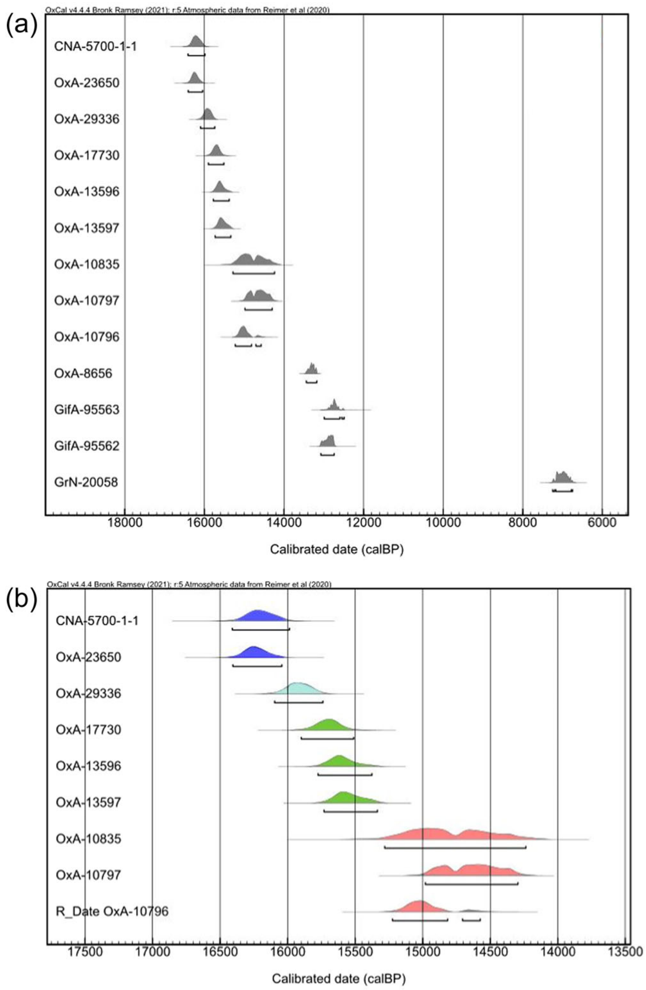

FIGURE 2 Radiocarbon dates calculated by the Oxcal online program (Reimer et al., 2020). (a) Radiocarbon dates obtained since 1987. (b) Radiocarbon dates appearing up to the Magdalenian human occupations. In red: Late Upper Magdalenian dates; in green: Upper Magdalenian dates and in blue: Middle Magdalenian dates.

The excavation works, conducted over an area of 40 m^2, have elucidated the spatial interconnections between the multiple vestiges and the structures evidenced. To date, 60 combustion structures have been identified, and they appear to be the focus of the productive, social and cultural activities of these communities. The Magdalenian occupations at the site reveal a great complexity, visible not only in the number and diversity of documented households but also in the variety of activities carried out in the cave, reflected in the typological and functional diversity of the lithic tools and the industry in hard animal tissues, which show the manufacture and repair of lithic (Langlais, 2010) and bone tools (Tejero, 2005), as well as the working of hides in the various phases of its operational chain, documented through use–wear analyses (Calvo, 2004). During the Upper Magdalenian occupations, the rock shelter area seems to have had a more sporadic domestic use, whereas during the Middle Magdalenian occupations, this area was as important as the cave considering the domestic activities.

3 | MATERIALS AND METHODS

3.1 | Macroscopic and geochemical approaches

First, a visual and micropalaeontological description was undertaken of 1176 lithic remains from the Middle Magdalenian occupations. All the retouched tools and cores ascribed to level III (n. 533) and an aleatory selection of nonretouched blanks (n. 643) from fieldwork seasons between 2015 and 2019 were considered for analysis. This macroscopic characterization was carried out using a stereo microscope Olympus model SZ61 (from 6.7 to ×45 magnification). Images were taken using a coupled Olympus SC30 camera. As the aim of the study was to analyse both geological and archaeological samples, nondestructive techniques were prioritized. Analyses took place at the SERP's laboratory at the University of Barcelona (Spain).

The second stage of this analytical approach involved geochemical analyses to quantify major, minor and trace components to be able to compare the raw materials of the chert artefacts with those from known geological outcrops. For this part of the study, 245 chert artefacts from level III were analysed by ED-XRF and 76 artefacts from the same level were studied by LA-ICP-MS. Archaeological tools without cortex and surface alterations were preferred.

With the aim of comparing results obtained after the analysis of archaeological samples, geological formations with cherts of similar characteristics to those of the artefacts from Cova del Parco were surveyed and sampled. The study involved 22 outcrops from 12 geological formations or units, with more than 430 samples being selected for geochemical analyses (Table 2). Only primary outcrops were considered for this study. To improve analysis time and to avoid surface alterations, geological samples were prepared in squares of 5 × 5 mm, removing cortex surfaces.

To analyse major and minor elements, ED-XRF was used. Analyses were performed at the Archéosciences-Bordeaux laboratory, Pessac, France. Eight element concentrations were quantified (Mg, Al, Si, P, K, Ca, Ti and Fe) using an X-ray fluorescence spectrometer SEIKO SEA 6000 VX (Orange et al., 2017), with fundamental parameters corrected by the granodiorite GSP2 from the US Geological Survey (USGS) international standard (Wilson, 1998). A 3 × 3 mm collimator was selected, and analysis time was set to 400 s for each measurement condition (three conditions with air or a He environment and a Cr or Pb filter were established). To check instrument calibration and accuracy, the JCh-1 chert standard from the Geological Survey of Japan (GSJ) was used (Imai et al., 1996). To prove and validate the formula used and to check instrument accuracy, a measurement with the JCh-1 chert standard was established, with the standard deviation obtained always being lower than 0.08 w%, thus validating the accuracy of the formula used (Sánchez de la Torre et al., 2017b).

To analyse trace elements, we used LA-ICP-MS at the Ernest Babelon laboratory, IRAMAT, Orleans, France. Elements were quantified using a Thermo Fisher Scientific Element XR mass spectrometer associated with a Resonetics RESOlution M50e ablation device. This

TABLE 2 Reference of the geological outcrops and the archaeological samples studied in this work by geochemistry and the number of samples analysed by energy-dispersive X-ray fluorescence (ED-XRF) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS).

Acronym	Outcrop/site	Formation/unit	Age	Type	ED-XRF	LA-ICP-MS
PC	Puente Candasnos	Bujaraloz-Sariñena Unit	Miocene	Lacustrine	23	20
VA	Valcuerna	Cinca Unit	Miocene	Lacustrine	20	-
LT	La Torraza	Lanaja-Castejón Unit	Miocene	Lacustrine	13	-
LM1	La Muela 1	Lanaja-Castejón Unit	Miocene	Lacustrine	20	-
LM2	La Muela 2	Lanaja-Castejón Unit	Miocene	Lacustrine	10	-
HOR	Campo de las Horgas	Lanaja-Castejón Unit	Miocene	Lacustrine	20	-
SB1	San Borombón 1	Pallaruelo-Sora Unit	Miocene	Lacustrine	20	-
SB2	San Borombón 2	Pallaruelo-Sora Unit	Miocene	Lacustrine	20	-
SQ	Santa Quiteria	Pallaruelo-Sora Unit	Miocene	Lacustrine	12	-
ALB1	Alberola 1	Alberola Unit	Oligocene	Lacustrine	20	20
ALB2	Alberola 2	Alberola Unit	Oligocene	Lacustrine	16	17
CDF	Castelló de Farfanya	Castelltallat Fm	Oligocene	Lacustrine	51	49
PERAL	Peraltilla	Castelltallat Fm	Oligocene	Lacustrine	23	20
ZURI	Zurita	Tremp Fm (2)	Maastrichtian	Lacustrine	18	13
MENT	Mentirosa	Tremp Fm (2)	Maastrichtian	Lacustrine	6	-
FONT	Fontllonga	Tremp Fm (1)	Maastrichtian	Evaporitic	-	19
ALI	Alins del Monte	Tremp Fm (1)	Maastrichtian	Evaporitic	-	30
CER	Cérizols	Bleu tertiary	Danian	Evaporitic	-	17
VSSM	Vessant Sud Sant Mamet	Tremp Fm (1)	Maastrichtian	Evaporitic	-	21
MONTG	Montgaillard	Flysch limestones	Turonian-Santonian	Marine	-	20
MONTS	Montsaunès	Nankin Fm	Maastrichtian	Marine	-	20
BUALA	Buala	Marly flysch	Campanian-Maastrichtian	Marine	-	20
PARCO	Cova del Parco	-	-	Lacustrine	245	-
PARCO	Cova del Parco	-	-	Evaporitic	-	20
PARCO	Cova del Parco	-	-	Marine	-	16

spectrometer has the advantage of being equipped with a dual-mode (counting and analogue modes) secondary electron multiplier (SEM) with a linear dynamic range of over nine orders of magnitude, associated with a single Faraday collector that allows an increase in the linear dynamic range by an additional three orders of magnitude. This feature is particularly important for the laser ablation analysis of lithic samples, as it is possible to analyse major, minor and trace elements in a single run regardless of their concentrations and their isotopic abundance. The ablation device is an excimer laser (ArF, 193 nm), which was operated at 7–8 mJ and 20 Hz, and only if saturation was observed were conditions reduced to 10 Hz. A dual-gas system with helium (0.65 L/min) released at the base of the chamber and argon at the head of the chamber (1.1 L/min) carried the ablated material to the plasma torch. Ablation time was set to 40 s: 10 s preablation to let the ablated material reach the spectrometer and 30 s collection time. Laser spot size was set to 100 µm, and only reduced to 80 or 50 µm if saturation was detected, and line mode acquisition was chosen to enhance sensitivity. Background measurements were run every 10–20 samples. Fresh fractures were analysed on geological samples to reduce potential contamination. Priority was given to characterizing large samples; thus, only one ablation line was carried out per specimen. However, if element spikes due to the presence of inclusions or heterogeneities were observed during analysis, the results were discarded, and a new ablation location was selected.

Calibration was performed using standard reference glass NIST610, which was run periodically (every 10–20 samples) to correct for drift. NIST610 was used to calculate the response coefficient (*k*) of each element (Gratuze, 1999, 2014), and the measured values of each element were normalized against 28Si, the internal standard, to produce a final percentage. Glass Standard

NIST612 was analysed independently of calibration to provide comparative data. Thirty elements were quantified (Li, Be, B, Mg, Al, Si, Ca, Ti, V, Cr, Fe, Ga, Ge, As, Rb, Sr, Y, Zr, Nb, Cs, Ba, La, Ce, Pr, Nd, Sm, W, Bi, Th and U).

3.2 | GIS analysis

The GIS analysis presents an approach to the study of the mobility of the Magdalenian groups of Parco in relation to the abiotic raw material catchment points at the end of the Last Glacial Maximum (LGM). The study area comprises the two Pyrenean slopes (north and south) and the Ebro Bassin. This offers an area of mobility that comes from the confirmed chert outcrops by geochemistry whose lithotypes are present in the archaeological site. According to the palaeolithic site function typologies proposed by Utrilla (1994), and due to the nature and use of the sites, the industries found and the evidence of biotic and abiotic resource acquisition, the Parco cave seems to be a seasonal camp (Mangado et al., 2007). Consequently, the type of exploitation characteristic of Magdalenian hunter-gatherers would correspond to a combination of logistic mobility (specific routes) and embedded procurement strategies, based on the monitoring of herds and biological cycles of species, or on the intensive exploitation of a habitat (Binford, 1979; Butzer, 1982; Marín Arroyo, 2008). In this way, it can be inferred that Magdalenian societies in the Pyrenees had resource acquisition circuits of hundreds of square kilometres, depending on the availability of biotic and abiotic resources. Thus, the purpose of this methodology is to make an approximation through GIS tools to observe the relationship of distances and physical effort that the contribution of the different siliceous resources to the Cova del Parco would entail for these societies.

In this sense, least cost path (LCP) and GIS studies have been carried out for the Magdalenian period in the northern part of the Iberian Peninsula (Cantabrian area) concerning the transport of animal materials (Arroyo, 2009; Gravel-Miguel & Wren, 2018) and abiotic materials (Fontes et al., 2016; García-Rojas et al., 2017; Prieto et al., 2016; Rissetto, 2012; Sánchez et al., 2016). On the other hand, in the Pyrenean area, a single study on the Magdalenian period (Mas et al., 2018) yields an analysis of visibility, insolation and energy cost of mobility in a surrounding area of 3000 m^2 from different sites in the Pyrenean Mountain range.

Thus, the present analysis proposes the application of three different methodologies in the approach to mobility studies: LCP based on slope digital elevation model (DEM) (Herzog, 2013; Llobera, 2000), LCP based on Tobler's Hiking Function (Lothrop et al., 2018; Tobler, 1993; White, 2015) and cost unit analysis (García-Rojas et al., 2017; Prieto et al., 2016; Sánchez et al., 2016). Combining these three methodologies aims to obtain a holistic vision of the possible mobility in the Pyrenean area at the end of the LGM. The comparison of the vector distances obtained from the LCP based on slope and the LCP based on Tobler's function allows us to obtain two mobility patterns: the first one based on energy cost efficiency and the second one based on time efficiency in pedestrian walking. Both types of routes generate a vector of distances that allows comparison of two variables (physical cost and time). This representation of distances offers a hypothetical vision of two mobility patterns that could have been used by the Magdalenian communities. To this is added the inclusion of an accumulated cost raster implemented by means of a physical cost raster, which allows the integration of these three-mobility analysis into a single map.

We have used QGis software (v. 3.22) and different plug-ins present in this software to proceed with the calculations for the study. The first step of the analysis is based on a DEM taken from the STRM-downloader complement, which provides terrain models from NASA's EARTHDATA service (30 × 30 m raster resolution). Once the models are combined for the Pyrenean and Ebro Valley area, the DEM raster is cropped using a vector polygon comprising the Ebro and Adour-Garonne river basins to delimit the study area.

The slope-based LCP analysis starts from the previous DEM raster on which we apply the *r.slope.aspect* complement of the GRASS plug-in (v. 7.8.7), which generates a friction surface composed of slopes tiles (in degrees). Manually, a null value is assigned to the raster surfaces with 0 slope value caused by the presence of water reservoirs and dams in the area to be studied. Thus, we prevent the route calculator from using these '0 slope highways' and its subsequent falsification of the route. After this modification, the *Least Cost Path* QGis function is applied to search for the optimal effort routes between the Cova del Parco and the outcrops.

Second, the analysis of the LCP based on Tobler's hiking function starts from the slope raster used above. Using the raster calculator, the slope raster is processed using the following formula: 6 × 2.71828^(−3.5 × Abs(Tan(('SlopeRaster' * 3.14159)/180) + 0.05))). The result obtained is another raster that will compose the friction surface of the next LCP analysis. In this case, the cells of the raster allude to an expression of optimal time to traverse distances, based on Tobler's formula (Tobler, 1993; White, 2015). Finally, the LCP analysis is applied on this raster, and we obtain the vector expression of the optimal distance as a function of the minimum time to cross a territory.

Third, the cumulative cost raster starts again from the first generated slope raster. A reclassification function is applied on the slope raster using a calibration curve (Prieto et al., 2016, fig. 2) to establish the correlation between the slope given in degrees and the physical effort required as a function. Once the reclassification of the slope raster is done, we obtain a new raster on which the GRASS *r.cost* function is applied, to obtain a Cumulative Cost Map that offers values from 0 to 47,134.047. In order to allow a proper graphical representation, these values are arbitrarily segmented into 70 'cost units (CU)' (673.34 each). These are the units that compose the basic unit of physical effort of this third analysis: the CU.

4 | RESULTS

4.1 | Macroscopic approach: First groups

Five different chert varieties were identified during the macroscopic study (Figure 3). Two of them (lithotypes 1 and 2) accounted for almost

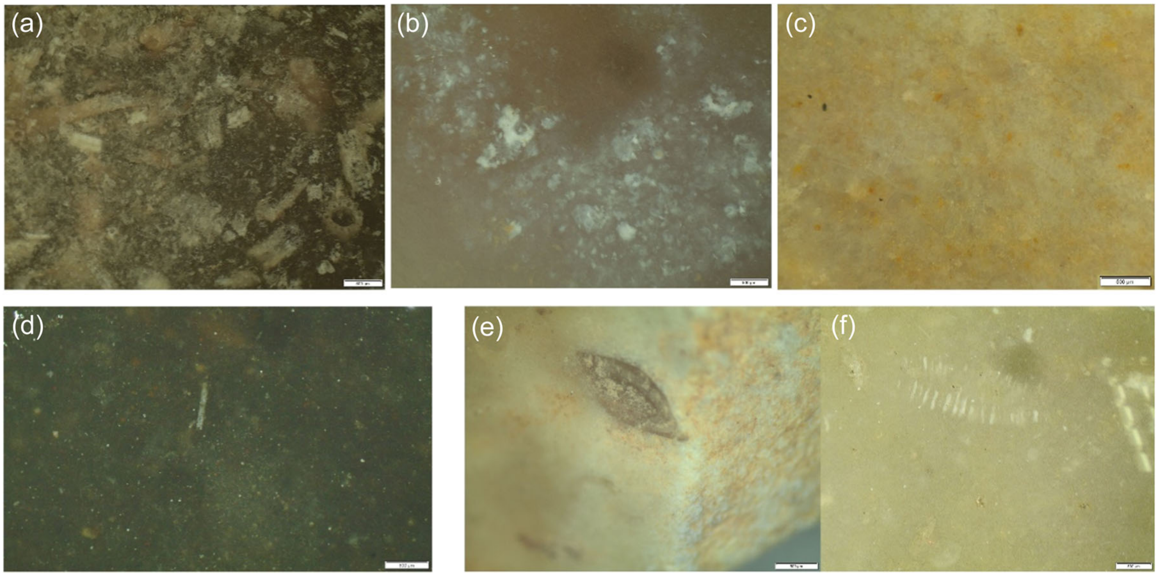

FIGURE 3 Views at the binocular stereoscope of the five chert types identified at the Middle Magdalenian human occupations. (a) Lithotype 1. (b) Lithotype 2. (c) Lithotype 3. (d) Lithotype 4. (e, f) Lithotype 5.

80% of the assemblage, with similar averages (45% for lithotype 1 and 43% for lithotype 2), whereas lithotypes 3 and 4 each represented 3% of the total studied set. Lithotype 5 was found sporadically, accounting for 1% of the assemblage, and 166 chert pieces remained undefined, as their macroscopic features could not be defined, mainly due to post-depositional alterations. These lithotypes have already been defined in previous studies (Sánchez de la Torre, 2015).

Five hundred and thirty-four chert samples were defined as belonging to *lithotype 1*. This chert type was macroscopically characterized by brownish colourations with a heterogeneous texture composed of inclusions of metal oxides, mud residues and rounded grains of detrital quartz. The micropalaeontological content comprised lacustrine bioclastic remains such as charophyte algae and gastropods. These cherts originated in a lacustrine sedimentary environment and up to seven geological formations outcropping in the Pre-Pyrenees (Tremp formation, Castelltallat formation and Alberola Unit), and the Middle Ebro Basin (Lanaja-Castejón Unit, Pallaruelo-Sora Unit, Bujaraloz-Sariñena Unit and Cinca Unit) presented nodular cherts with similar macroscopic features as the defined lithotype.

Five hundred and nine chert remains were defined as belonging to *lithotype 2*. This chert was characterized by the stereoscopic microscope as originating in a lacustrine hypersaline environment; the macroscopic texture was quite homogeneous, with the typical colourations oscillating between pinkish and greyish. Only metal—probably iron—oxides and lenticular gypsum pseudomorphs were identified as inclusions, and no evidence of bioclastic remains appeared. Macroscopically similar cherts appear embedded within the limestones from the Garumnian facies of the Tremp formation, largely outcropping in the Pre-Pyrenean region, close to the archaeological site.

Thirty-three chert samples were defined as *lithotype 3*. This chert type, with orangish to yellowish colourations, was macroscopically defined with a heterogeneous texture with abundant metal oxides and grains of detrital quartz. The micropalaeontological content included abundant sponge spicules and scarce macroforaminifera such as *Siderolites*. This chert type is macroscopically similar to two chert units appearing in the northern slope of the Central Pyrenees: the Montgaillard flysch cherts from the Turonian-Santonian and the Montsaunès-Buala cherts from the Nankin formation, belonging to the Middle Maastrichtian.

Thirty-nine chert remains were defined as *lithotype 4*. This silicification was characterized by blueish to blackish colourations, with a macroscopic texture composed of inclusions of metal oxides, calcite or dolomite rhombohedral crystals, abundant detrital quartz crystals and probably organic matter as impurities. The micropalaeontological content was constituted by abundant sponge spicules and small foraminifera (globigerinids), indicating marine sedimentation as the origin. Similar macroscopic cherts to those of lithotype 4 were found in the southern Central Pyrenean region, belonging to the Agua-Salenz formation.

Eleven chert tools were defined as *lithotype 5*. This last macroscopic variety possessed mostly yellowish colourations with a homogeneous texture characterized by the presence of scarce micritic remains and metal oxides. The micropalaeontological content was defined by the abundance of macroforaminifera. *Lepidorbitoides* as well as *Siderolites* and bryozoaires were identified, indicating a marine sedimentation environment. The macroscopic features of this lithotype allowed direct connection with the Maastrichtian cherts outcropping in Audignon, mainly known as Chalosse cherts.

4.2 | Geochemical approach: Connecting sources

Geochemical methods were used to establish a direct connection between the most exploited chert types in level III from Cova del

Parco and the potential sourcing areas. ED-XRF was used to quantify major oxides of lacustrine cherts, which were macroscopically similar to seven geological formations outcropping in the first Pre-Pyrenean Mountain ranges from Lleida and Huesca provinces (Tremp formation, Castelltallat formation and Alberola Unit) and the Middle Ebro basin (Lanaja-Castejón Unit, Pallaruelo-Sora Unit, Bujaraloz-Sariñena Unit and Cinca Unit). A detailed macroscopic, petrographic and geochemical description of these formations can be found in Sánchez de la Torre et al. (2017b, 2019a).

We just analysed the lacustrine chert type by ED-XRF, as previous studies had revealed that this technique was not discriminant when analysing other chert types (Sánchez de la Torre et al., 2017b). Eight oxides were measured with ED-XRF (MgO, Al_2O_3, SiO_2, P_2O_5, K_2O, CaO, TiO_2 and Fe_2O_3) but data relating to P_2O_5 were sparse, as values were frequently below the equipment's detection limits. The raw data with the median values from each geological outcrop and the values for all the archaeological samples in w% can be found in Supporting Information S1: File S1. Results show that this approach is not conclusive, but that some formations can already be discarded at the major and minor component level. A scatter plot with the three main components (Al_2O_3, Fe_2O_3 and SiO_2) (Figure 4) was constructed. It can be observed that several geological formations overlap with the main dispersion area of the archaeological cherts (Figure 4a), the lacustrine cherts from Cova del Parco thus being quite similar to geological cherts from the Lanaja-Castejón, the Pallaruelo-Sora and the Bujaraloz-Sariñena Units as well as those from the Castelltallat and the Tremp formations. In contrast, cherts from the Cinca Unit, the Alberola-Tartareu Unit as well as some specific outcrops from the Lanaja-Castejón Unit (La Torraza outcrop), the Pallaruelo-Sora Unit (Santa Quiteria) and the Castelltallat

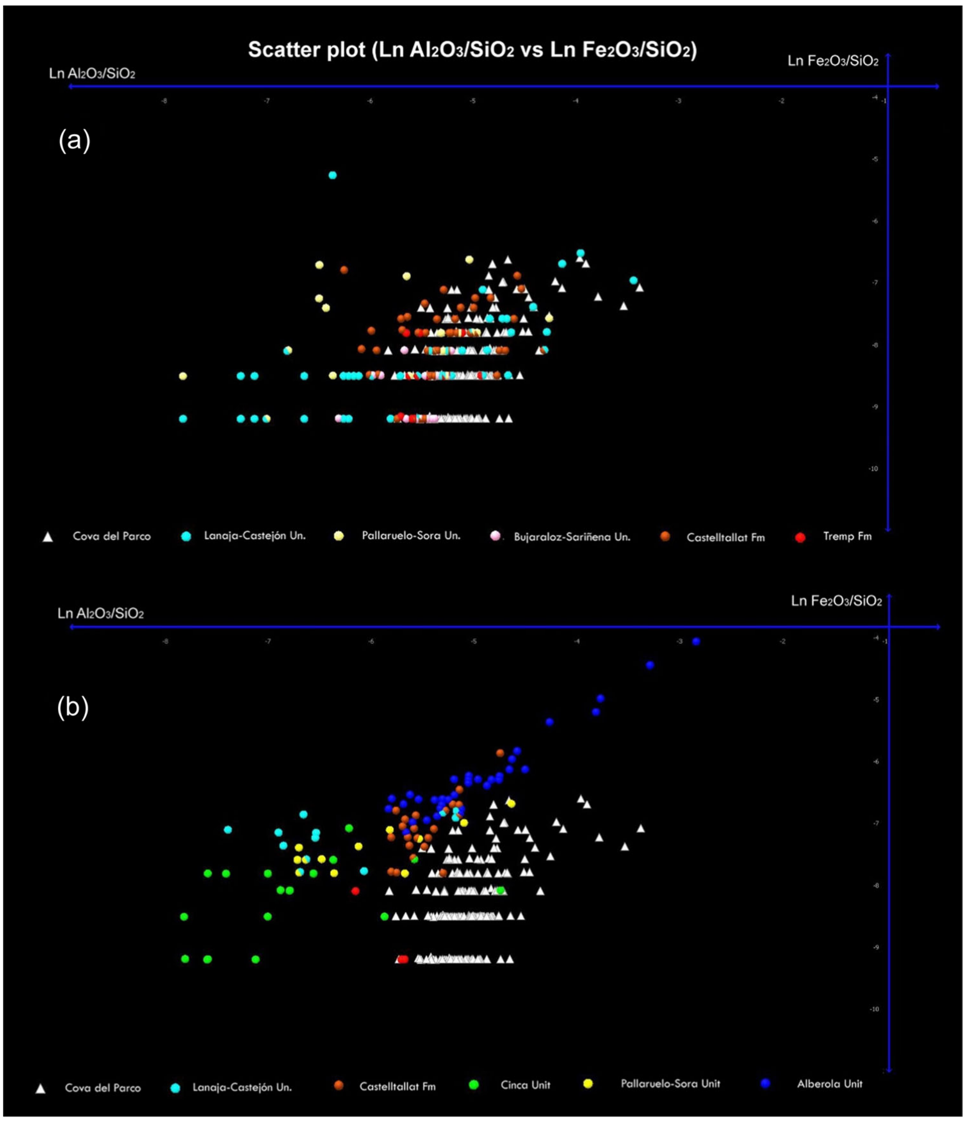

FIGURE 4 Scatter plot concerning Ln Al_2O_3/SiO_2 versus Ln Fe_2O_3/SiO_2 for data obtained by energy-dispersive X-ray fluorescence. (a) Geological formations mostly fitting with the lacustrine archaeological samples. (b) Geological formations not fitting the main dispersion area of the lacustrine archaeological samples.

formation (Alfarràs and Peraltilla outcrops) could already be discarded, as the main dispersion of these geological sources did not fit with the lacustrine archaeological cherts.

As ED-XRF was not conclusive for the lacustrine cherts, they were also analysed by LA-ICP-MS. The median values and the standard deviation for each geological outcrop and the values for all the archaeological cherts in ppm can be found in the Supplementary Raw Data file. The LA-ICP-MS results suggest that some trace elements may be relevant for distinguishing between sources. Regarding the lacustrine cherts, the values for Ln As, U and W were used for constructing a scatter plot (Figure 5). It can be easily observed that geological samples from the Tremp formation and the Bujaraloz-Sariñena Unit do not fit with the main archaeological dispersion (Figure 5b). In contrast, geological samples from the Castelltallat formation (Castelló de Farfanya outcrop) and from the Lanaja-Castejón Unit (La Muela outcrops) and the Pallaruelo-Sora Unit (San Borombón outcrops) appear in the same dispersion area as the archaeological samples (Figure 5a). Nevertheless, there is an overlap between some of the geological sources. For this reason, a Discriminant Analysis with the three potential sources was performed (Figure 6). In this case, the three geological sources can be distinguished; however, an overlapping area remains between some samples from the Lanaja-Castejón Unit and the Pallaruelo-Sora Unit. After this analysis, we can state that the studied lacustrine cherts from Cova del Parco seem to have different origins, with some samples directly linked to the Castelltallat formation cherts, but there

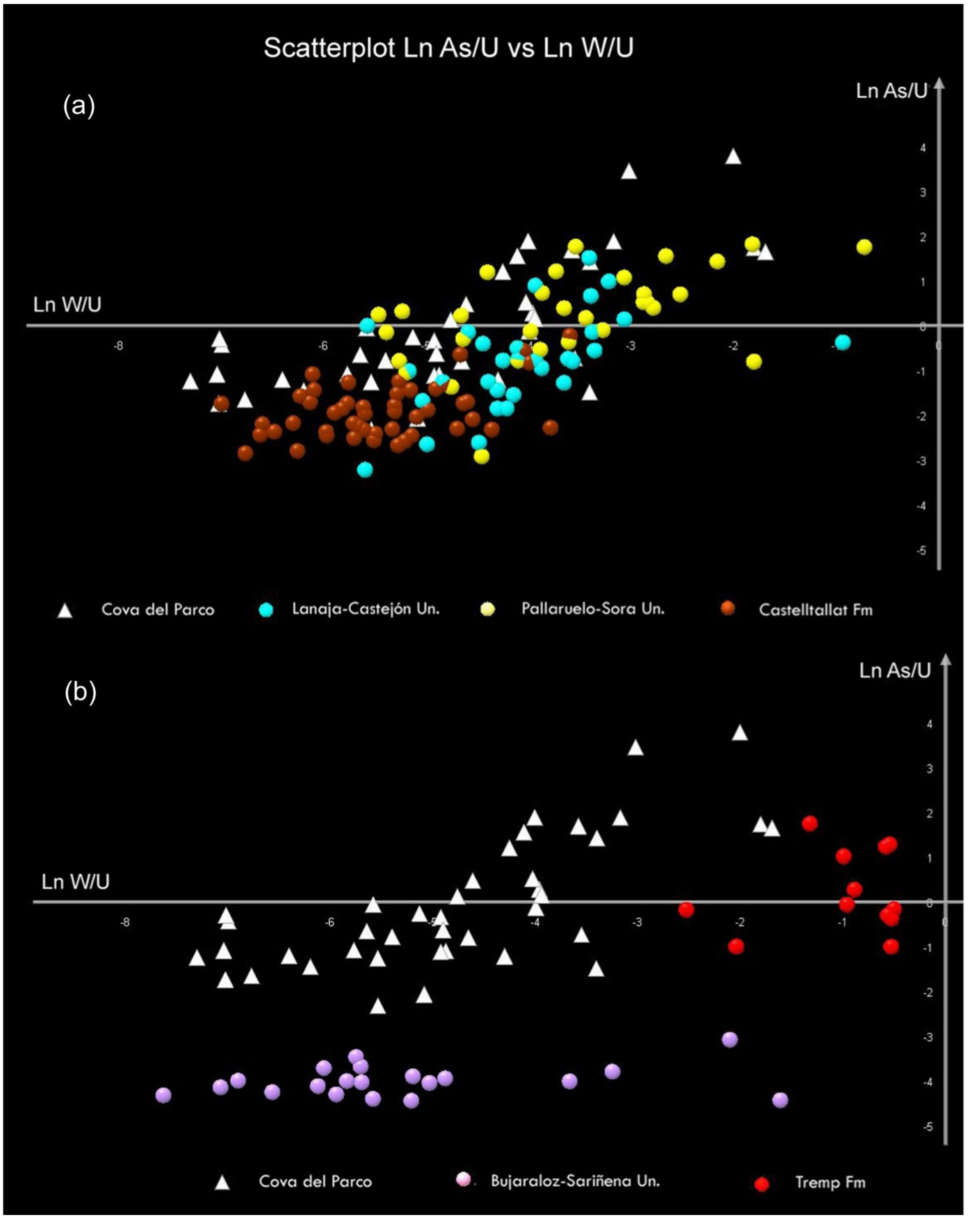

FIGURE 5 Scatter plot concerning Ln As/U versus Ln W/U for data obtained by laser ablation inductively coupled plasma mass spectrometry. (a) Lacustrine archaeological cherts and the geological formation cherts similar to them. (b) Lacustrine archaeological cherts and geological formation cherts different from the main dispersion area.

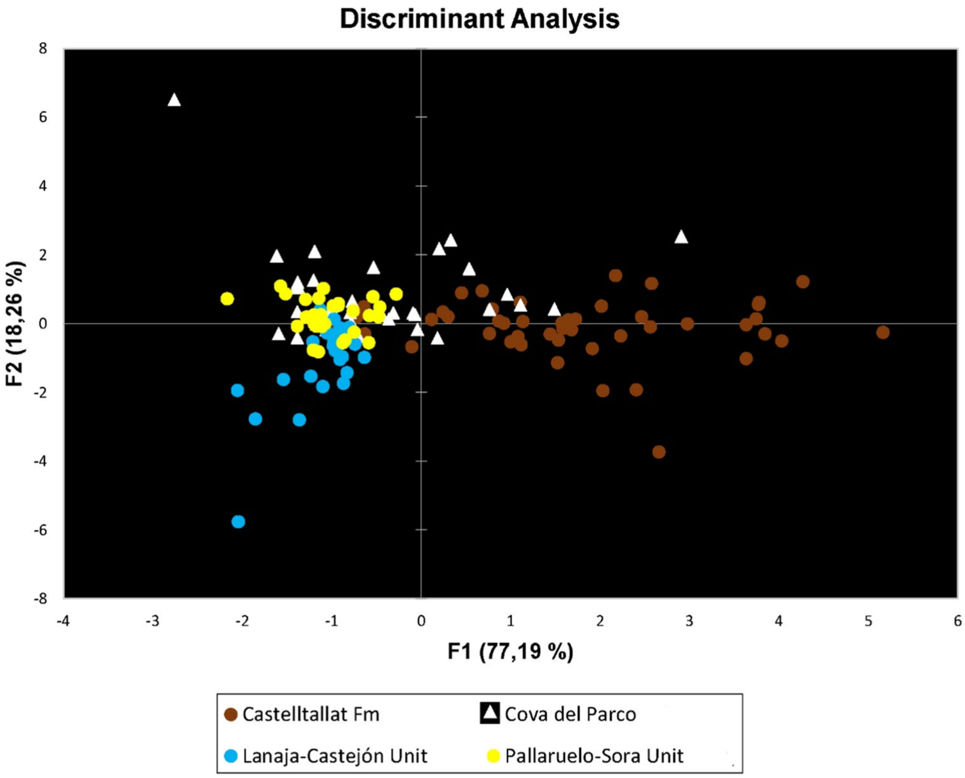

FIGURE 6 Discriminant analysis obtained with laser ablation inductively coupled plasma mass spectrometry data for U and As values with the lacustrine archaeological cherts and the three most suitable geological formations according to the previous analyses.

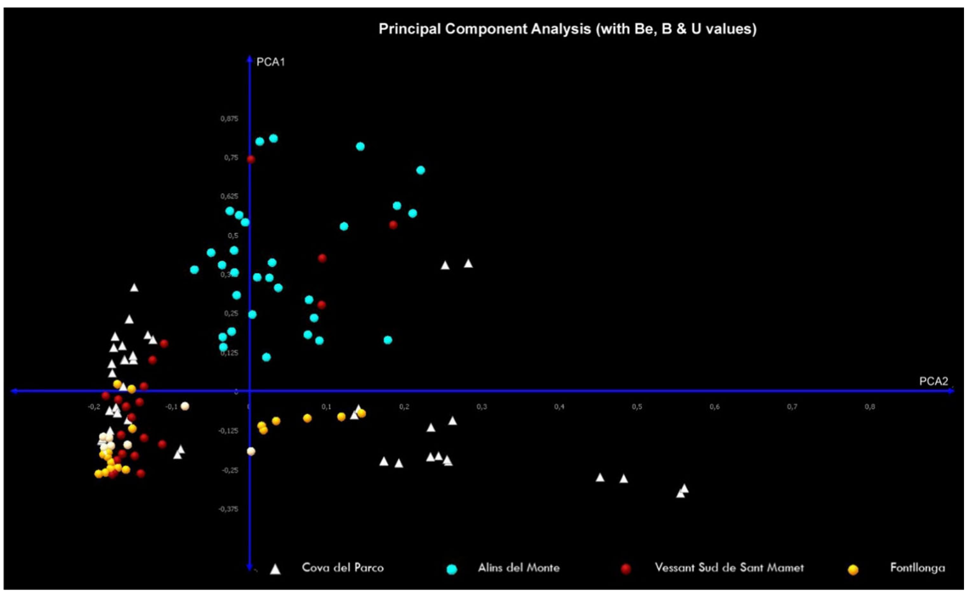

FIGURE 7 Principal component analysis with laser ablation inductively coupled plasma mass spectrometry data for Be, B and U values with the evaporitic archaeological cherts and the three studied geological chert outcrops (Fontllonga, Vessant Sud de Sant Mamet and Alins del Monte).

are some samples that may have their origin in the lacustrine units from Lanaja-Castejón and Pallaruelo-Sora, outcropping in the Middle Ebro Basin (Zaragoza province).

With type 2 evaporitic cherts, the geochemical analysis by LA-ICP-MS revealed interesting data. The archaeological samples from Cova del Parco were compared with geological samples from three different outcrops from the Garumnian facies of the Tremp Formation: Alins del Monte, Vessant Sud de Sant Mamet (VSSM) and Fontllonga (Sánchez de la Torre, 2015). A principal component analysis was performed taking into consideration the Be, B and U values (Figure 7). There seem to be different chemical signatures for the archaeological samples. Many of them coincide strongly with VSSM's samples, which is also the closest outcrop to the site. However, there is another group of samples that does not fit with any of the geological sources studied, meaning that other geological sources not yet assessed may have been frequented by Magdalenian societies. What seems clear is that the geological outcrop from Alins del Monte was not part of the territory where they acquired their lithic raw materials.

The type 3 marine cherts were also studied through LA-ICP-MS. This chert type was macroscopically similar to three geological units outcropping on the northern slope of the Central Pyrenees: the Turonian-Santonian flysch cherts from Montgaillard, the Campanian-Maastrichtian flysch cherts from Buala and the Maastrichtian cherts from the Nankin formation outcropping in Montsaunès. More accurate information about these formations and their geochemical signature can be found in Sánchez de la Torre et al. (2019b). Previous studies have shown that with specific trace elements, the three sources can be distinguished easily. Thus, in the scatter plot showing Ln Ti/Sr versus Ln Th/Sr, the samples from Cova del Parco directly connect with the main dispersion from the Montgaillard geological samples, with just two outliers that might fit with the main dispersion of the Buala geological outcrop (Figure 8).

4.3 | GIS analysis: Connecting paths of mobility

The data obtained from the GIS analysis show the influence that the relief may have had on the supply patterns of the Cova del Parco after the LGM. For this purpose, we have considered those outcrops that had been confirmed through geochemical analysis with the lithotypes present in the Middle Magdalenian sequence of Parco.

Generally, we can compare the two types of optimal routes (Table 3, Figures 9 and 10) generated by the slope-based LCP analysis and the Tobler function-based LCP. The analysis raster consisted of physical cost and time, respectively. Overall, the resulting distances allow us to observe that the routes obtained by Tobler's function are significantly shorter than those obtained by slope-based LCP: Between 12% and 40% for distances to outcrops for lithotype 1; 12% for lithotype 3; 24% for lithotype 4%; and 5% for lithotype 5. The exception is marked by the outcrops of lithotype 2, whose distances in LCP are smaller than those with Tobler's function.

At the topographic level, the route obtained by LCP slope tends to use the valley bottoms in the mountainous sections, in contrast to the Tobler route, which uses the high slopes of the hills surrounding these valleys, hence the shortening of distance that occurs in the latter model. In this sense, the distance variations between the slope LCP, Tobler's LCP and Euclidean routes remain equivalent in their differences from outcrop to outcrop. This is why, to categorize the different groups of outcrops, we consider the use of the 'CU' proposed by Prieto et al. (2016) to be more useful than the hypothetical routes obtained through the previous analyses. This is because the accumulated cost through the magnitude of UC is a variable that can be applied to any territory without being conditioned by a hypothetical itinerary that, in the case of the end of the Pyrenean Pleistocene, would be very difficult to confirm. Therefore, we will use the general framework of UC to carry out the distance categorization of the flint groups confirmed in the Middle Magdalenian of Parco.

In general terms, three 'dispersion modes' of the chert outcrops identified can be established according to the CUs assigned to each formation.

The first 'local' group is made up of cherts from the VSSM and Fontllonga evaporitic outcrops of lithotype 2, with four CU, as well as those belonging to lithotype 1 of the Castelltallat formation, with 5–6 CU. This latter group of lacustrine cherts has been considered by previous studies (Langlais, 2010; Mangado, 2005; Sánchez de la

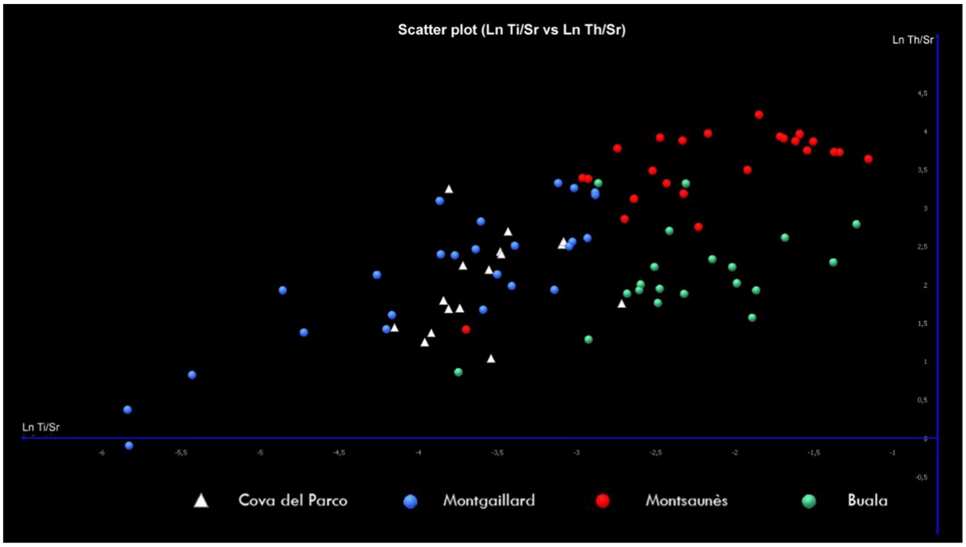

FIGURE 8 Scatter plot with laser ablation inductively coupled plasma mass spectrometry data concerning Ln Ti/Sr versus Ln Th/Sr for the marine type 3 archaeological cherts and the compared geological outcrops (Montgaillard, Montsaunès and Buala).

TABLE 3 Data concerning the cost unit (CU) raster values, CU segmented values, least cost path (LCP) (slope), LCP (Tobler's hiking function), Euclidean distances and distance reductions between LCP slope and LCP Tobler's distances (%).

Outcrop	CU (raster value)	CU (segmented)	LCP distance (km)	Tobler's hiking distance (km)	Euclidean distance (km)	Distance reduction LCP versus Tobler's hiking distance (%)
Fontllonga (T2)	2775.732328	4	7.44	7.76	6.83	−4
VSSM (T2)	2831.57459	4	18.51	22.55	8.72	−22
Castelltallat (T1)	3645.672369	5	37.88	29.67	21.23	22
Castelltallat (T1)	3774.499496	6	38.52	30.78	22.21	20
Castelltallat (T1)	3954.83158	6	37.14	31.45	22.74	15
Castelltallat (T1)	3351.04934	5	55.40	33.13	24.18	40
Castelltallat (T1)	3407.210867	5	59.91	35.74	26.49	40
Castelltallat (T1)	3442.334514	5	50.00	37.63	28.23	25
Castelltallat (T1)	3549.56754	5	53.29	46.89	30.66	12
Lanaja-Castejón (T1)	7934.029018	12	318.15	250.70	175.85	21
Lanaja-Castejón (T1)	10,189.92239	15	255.54	178.83	120.45	30
Lanaja-Castejón (T1)	10,287.9253	15	317.90	249.64	175.06	21
Pallaruelo-Sora (T1)	6728.298474	10	224.60	157.64	103.68	30
Pallaruelo-Sora (T1)	9944.555305	15	321.84	254.48	177.64	21
Pallaruelo-Sora (T1)	10,013.00638	15	318.52	250.15	173.40	21
Pallaruelo-Sora (T1)	9975.727212	15	318.76	250.21	173.46	22
Pallaruelo-Sora (T1)	10,490.2548	16	308.72	249.99	173.34	19
Agua-Salenz (T4)	10,734.01877	16	152.28	116.37	65.14	24
Montgaillard (T3)	24,756.1587	37	263.75	231.97	150.86	12
Chalosse1 (T5)	26,663.63123	40	376.27	355.65	237.24	5
Chalosse2 (T5)	27,945.11053	42	421.18	398.09	257.45	5

Torre, 2015) as lithological groups of regional character because they are at Euclidean distances greater than 20 km. However, observing the CUs as a measure of territorial approximation, it is possible to establish a pattern of supply of lithotype 1 similar to that present in the cherts of evaporitic origin of lithotype 2. In other words, we are dealing with a group of cherts of a local–immediate nature, accessed through the Segre and located between the foothills of the Serra del Montsec and the Serra Llarga.

The second 'regional' group is made up of the lacustrine chert formations of Lanaja-Castejón and Pallaruelo Sora from the Middle Ebro Valley, framed within lithotype 1, with between 12 and 15 CU. Together with these, lithotype 4 from the Agua-Salenz formation of the Central Pyrenees is included with 19 CU. However, large differences in the scale of the optimum distances can be observed, mainly due to the regional and medium-distance orography present in the access to these outcrops. The supply of the formations of the Middle Ebro Valley occurs on a southwest–northeast axis, through the Ebro and Segre Valleys. The moderate CU value, in this case, is due to the long distances (250–320 km on LCP; 157–250 km on Tobler's hiking route) required to access these formations. In contrast, the Agua Salenz formation, located close to Parco (152 km on LCP; 116 km on Tobler's), is placed in a fully mountainous orographic context.

The third 'allochthonous' group is made up of the outcrops coming from the northern slope of Pyrenean Range: type 3 from Montgaillard, with 37 CU, and type 5 from Chalosse, with 40–42 CU. Both groups, which are in the minority in the Middle Magdalenian record of Cova del Parco, allow us to observe a very specific supply dynamic linked to sporadic exchanges in the Pyrenean environment. The high cost of these formations is undoubtedly due to the need to cross the Pyrenean chain to the northwest.

5 | DISCUSSION

In Cova del Parco, chert was almost the only rock used to manufacture lithic tools. The macroscopic analysis of the chert samples recovered in the Middle Magdalenian human occupation

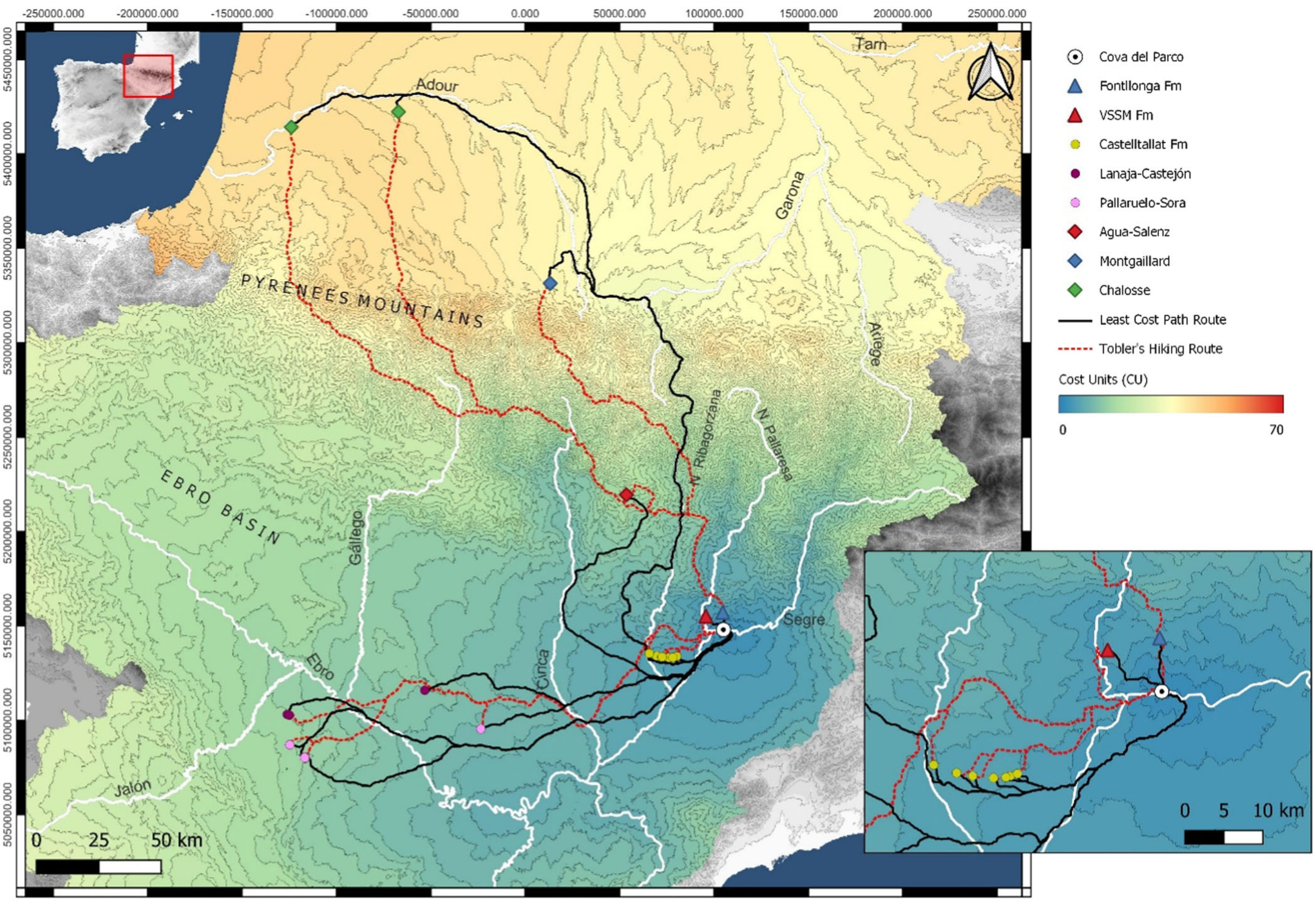

FIGURE 9 Cost map including least cost path (LCP) (slope) and LCP (Tobler's hiking function) of Cova del Parco and the outcrops considered after the geochemical analysis.

(level III) has allowed us to define as many as five different varieties in terms of the textural and micropalaeontological content. In some cases, the presence of specific inclusions and bioclastic remains has allowed us to directly connect the archaeological samples with a specific geological unit (in the case of lithotypes 4 and 5). However, lithotypes 1, 2 and 3 were subjected to geochemical analysis to discriminate the different sources and thus establish a direct connection between archaeological and geological samples. The application of ED-XRF to lithotype 1—lacustrine cherts—was interesting, as some differences appeared between the sources in the quantification of major and minor elements. Nevertheless, it was the application of LA-ICP-MS that made it possible to discriminate between the three chert types studied (lithotypes 1, 2 and 3) and thus make the connection with specific units and outcrops.

The analysis of lacustrine cherts defined as lithotype 1 has allowed us to establish a relationship between the archaeological cherts with the geological units of Castelltallat formation (20–28 km in Euclidean distance), located in the first Pre-Pyrenean foothills in contact with the Ebro Basin, and the Lanaja-Castejón and Pallaruelo-Sora Units, both located in the Middle Ebro Valley, more than 100 km from the site in Euclidean distance. It seems clear that lithotype 1 was mainly acquired at the Castelltallat formation. However, regarding the elemental chemical composition, a large part of the studied samples presents more similarities with the Middle Ebro Basin formations of Lanaja-Castejón and Pallaruelo-Sora, where there are many outcrops of chert of exceptional quality (extremely fine surfaces without internal fissures). The GIS analysis for this chert type establishes that the procurement in the Castellatallat formation must be considered local in view of the CU, whereas the procurement in the Middle Ebro formations must be considered regional, due to the Ebro Basin plain separating Cova del Parco from these outcrops.

Cherts defined as lithotype 2, originating in a hypersaline lacustrine environment, can be directly related to the Garumnian facies from the Tremp formation mainly outcropping in the southern central-eastern Pre-Pyrenees. The geochemical analysis aimed to establish differences between different outcrops. In this regard, while ED-XRF did not provide useful results, LA-ICP-MS analyses allowed a distinction between sources based on specific trace elements. Whereas some archaeological samples do not fit with any of the outcrops studied, most are located in the dispersion area of VSSM and Fontllonga outcrops. These outcrops are in the immediate local context from Cova del Parco, requiring low effort-cost to access them.

Finally, the marine cherts defined as lithotype 3 have their origin on the northern slope of the Central Pyrenees. Whereas the ED-XRF

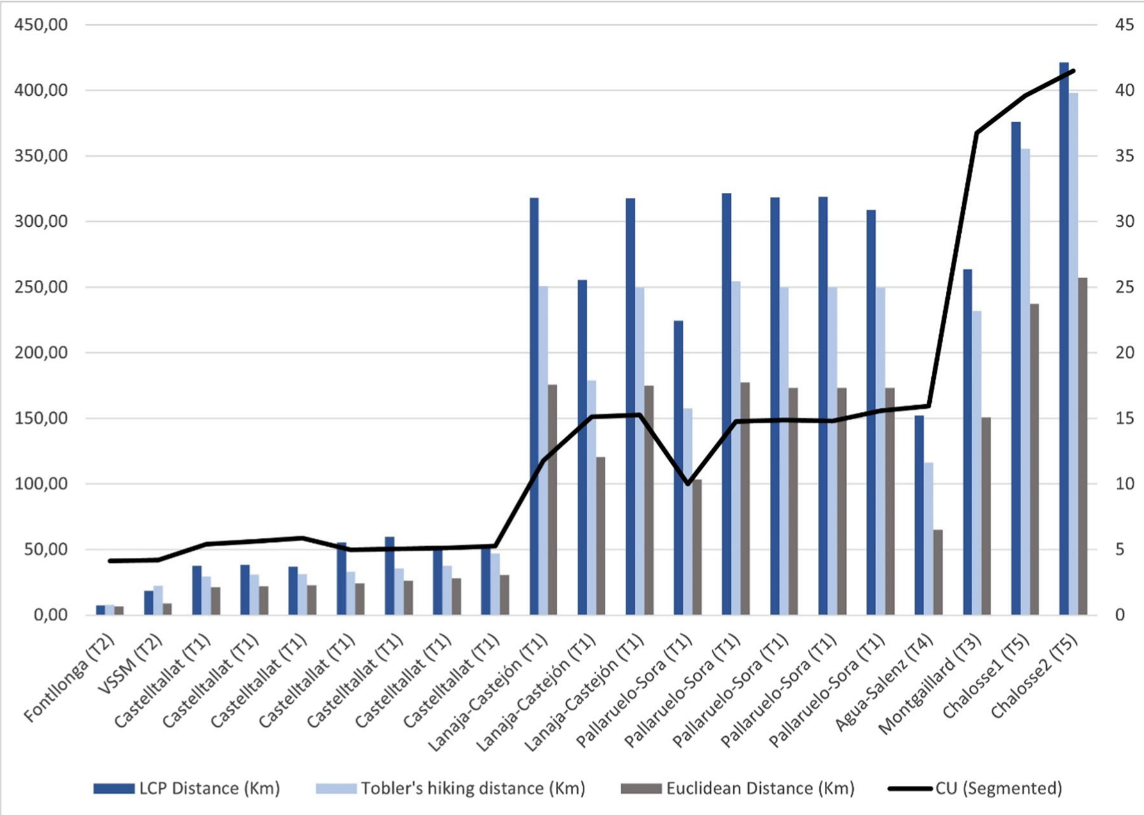

FIGURE 10 Composite plot of least cost path (LCP) (slope), CLP (Tobler's hiking function) and Euclidean distances (bars) and cost units (line) of the studied outcrops.

analysis did not yield useful data for discriminating between sources, the application of LA-ICP-MS allowed discrimination because of specific trace elements. It seems clear that, except for one sample, the studied set ascribed to this lithotype has its origin in the Montgaillard flysch cherts. The GIS analysis revealed that they should be considered as an allochthonous chert in view of the high CU, caused by the orographic conditions.

All this makes up a supply horizon, which, from the Cova del Parco, fans out into two main routes. The first, to the southwest, follows the Segre and Ebro basins. The second, towards the northwest, requires an entry into the Pyrenees Mountain range without having to go around its western limits, meaning that it was possible, in view of this analysis of mobility based on relief, to cross the Pyrenees after the LGM. It is interesting again to highlight the fact that the GIS analysis establishes the connection between Cova del Parco and Montgaillard flysch cherts (lithotype 3) and Chalosse cherts (lithotype 5) crossing the Central Pyrenees through the Vielha pass (using LCP slope analysis), a crossroad traditionally used to traverse the Pyrenean Mountain Range in this area. Thus, it should be emphasized that LCP slope and Tobler's hiking route analysis has established that the most efficient way (in terms of effort and time, respectively) to gain access to these allochthonous outcrops may have been by crossing the Pyrenees directly, and not crossing them in the western foothills of the Basque Country, especially in order to access the Chalosse chert group.

Regarding the presence of glaciers in the Pyrenees for the Magdalenian period, Calvet et al. (2011) report evidence of rapid deglaciation events in the Pyrenean glacial valleys at the end of the LGM. The study of Noguera Ribagorzana passes, specifically the moraines of Santet (1560 m asl) and the Redo d'Aigüestortes lake (2110 m asl) (Rodés et al., 2008), allows us to observe episodes of ice absence (morainic regression) between 17 ± 0.7–14.6 ± 1 ka B.P. and 13.47 ± 0.06 ka B.P., respectively. Delmas (2005) reports similar dynamics for the Carlit massif around 16.5 ka B.P. in the eastern Pyrenees. Therefore, a hypothetical route between the Pyrenees could have been possible for Middle Magdalenian chronology, regardless of the raw material acquisition strategy used to obtain the allochthonous chert types.

The large-scale mobility networks regarding the procurement of lithic raw materials that have been observed in Cova del Parco were also seen at other sites that also present human occupations from the Upper Palaeolithic. In almost all cases, a mobility between both Pyrenean slopes was attested regarding the nature of the lithic set (Sánchez de la Torre et al., 2019b, 2020, 2023). Thus, these studies confirm a large territoriality for these hunter-gatherer populations that seem to largely move during their annual mobility cycle.

In this sense, it should be noted that the nature of the acquisition of lithic raw materials in Magdalenian times is part of mixed strategies for the capture of biotic and abiotic resources, whether they are integrated strategies, specific or logistical strategies or supplies made by exchanges (Binford, 1979; Terradas, 2001). Although our study focuses on establishing hypothetical site-outcrop acquisition routes, it is important to highlight that the procurement of the different lithotypes present in the Cova del Parco must have necessarily responded to the combination of these different types of collection strategies, such as those observed in other Magdalenian contexts (Rensink, 1995). Thus, in a general way, we could inscribe the collection of lithotypes 1, 2 and 4 within specific procurement (lithotype 2) or integrated within other socioeconomic activities (lithotypes 1 and 4), while lithotypes 3 and 5, coming from the northern slopes of the Pyrenees, must have been taken using networks and dynamics of social and economic exchange of the human groups surrounding the Pyrenean chain, where crossing from one slope to another could have been possible. Consequently, we are dealing with areas of direct economic capture of several tens of kilometres around the site and a network of socioeconomic exchanges that would extend throughout the Pyrenean area and the Ebro Bassin region.

Considering that we are studying nomadic societies with an important stationarity, it must be considered that humans occupying Cova del Parco during specific moments in the Middle Magdalenian probably moved to the Middle Ebro Basin as well as to the northern Pyrenees during their annual cycle. Thus, future studies attempting to connect different archaeological sites with similar chronocultural occupations will be essential to precisely identify the territoriality of these hunter-gatherer societies at a larger scale.

6 | CONCLUSIONS

The complete geochemical and GIS analysis described in this paper demonstrates the potential of these characterization techniques for understanding prehistoric societies. In this paper, through the study of the chert assemblage recovered at the Middle Magdalenian human occupation from Cova del Parco, we have been able to obtain a much more precise map of the relationships and contacts that occurred at the end of the Palaeolithic on the southern slope of the Pyrenean Mountain range. Together with the GIS cost analysis and the possible theoretical optimal routes that might have emerged during this period, we can now infer that the Pyrenean valleys probably acted as communication routes, not as physical barriers for the movement of these hunter-gatherer populations after the LGM. Although some of these issues had already been raised in previous studies, the greater precision in the location of the outcrops presented in this study allows us to obtain a higher-resolution picture of the socioeconomic interactions that took place after the Pyrenean LGM. Future studies involving the analysis of other similar chronocultural human occupations in this mountain range are now indispensable for improving our understanding of the relationship between Upper Palaeolithic human groups and this mountainous area.

AUTHOR CONTRIBUTIONS

Luis M. Jiménez: Conceptualization; methodology; software; formal analysis; supervision; investigation; writing—review and editing; writing—original draft. **Xavier Mangado**: Investigation; supervision; writing—review and editing; project administration. **Cynthia B. González**: Investigation; writing—review and editing; supervision; project administration. **François-Xavier Le Bourdonnec**: Investigation; writing—review and editing; supervision; resources. **Bernard Gratuze**: Investigation; writing—review and editing; supervision; resources. **Josep M. Fullola**: Investigation; writing—review and editing; supervision; project administration. **Marta Sánchez de la Torre**: Formal analysis; supervision; conceptualization; methodology; writing—original draft; writing—review and editing; investigation; software; funding acquisition; project administration.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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