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Quantifying accessibility to Palaeolithic rock art: Methodological proposal for the study of human transit in Atxurra Cave (Northern Spain)

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ABSTRACT

The systematic evaluation of accessibility to different sectors in caves with Palaeolithic rock art is crucial to interpret the contexts of prehistoric human activity that took place inside them, especially if focused on the areas that are harder to reach. 3D models have been employed in a GIS to process spatial information, calculate numerical cost values and estimate optimal transit routes or needed times to reach several sectors inside a cave, based on morphological features and movement types. These have been obtained through empirical observations and experimental archaeology. Previous geomorphological studies are necessary to determine any geological or anthropic changes that may have occurred in the endokarst since its use in the Upper Palaeolithic. The method has been applied in Atxurra Cave, with satisfactory results, and the accessibility to different archaeological sectors has been compared objectively. This will enable the objective and quantitative assessment of accessibility to the deep sectors of other prehistoric caves in the future, and thus establish recurring or specific patterns among the human groups that created the Ice Age art.

1. Introduction: precedents in research and objectives

The location of parietal art is a determining factor to reach its meaning. As P. Bahn (2011: 354) points out, "*it is inaccessibility of different kinds which seems to be a crucial factor in most 'private' art*". Participation in such a relevant social activity is conditioned, among other cultural factors (Fritz et al., 2016a; Rivero 2016), by the characteristics of access to the rock art. During the first century after the discovery of prehistoric rock art caves in 1879, research concentrated on establishing the chronology of the artistic manifestations and on unravelling their meaning (Breuil 1952); and only a few authors insisted on the role of the cave in the structure and composition of prehistoric art (Laming-Emperaire 1962; Lorblanchet 2010). Palaeolithic cave 'sanctuaries' were also divided into different areas depending on their location inside the endokarst (entrance, centre, end, secondary passage, etc.). Highlighting cases, like Etxeberri (south-western France), where the route to the decorated area is very dangerous and difficult, even using modern speleological equipment (Leroi-Gourhan 1965).

"La Paleospeleologie" (Rouzaud 1978) was the first work to present a common methodology applicable to the study of accessibility in different caverns. It defines several types of areas inside the caves depending on the archaeological evidence found in them or the presence or absence of natural lighting. In addition, optimal circulation paths are classified (in qualitative terms) according to the size of the passages or the consistency and inclination of the cave floor. Later, D. Vialou (1986: 335) made the first gradual categorization, in qualitative terms (based in the distance between the entrance and the rock art panels), in order to compare accessibility in different decorated caverns.

In recent years, new research on Palaeolithic underground appropriation has appeared. Pastoors and Weniger (2011) propose a series of methods for spatial studies in decorated caves, developing the pioneering ideas of F. Rouzaud. Similarly, the difficulty of access to different panels has recently been assessed according to the method of movement through the cave (Ochoa and García-Díez 2018). In another

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current example, researchers consider the difficulty and danger in accessing the figures in Lascaux (France) to discuss the feasibility of using CST (Costly Signalling Theory) techniques in the study of parietal Palaeolithic art (Gittins and Pettitt 2017). In Cussac Cave (France) (Jouteau et al., 2019), the authors contemplate the accessibility and other morphological features (wall morphology, the visibility of the panels, the size of the sectors, etc.) to distinguish different groups with Factor Analysis of Mixed Data (FAMD) and detect patterns in the choice of rock art locations. In this case, accessibility is classified by the method of movement (standing, crouching, etc.) and the level of difficulty (easy, delicate or difficult), or morphological features measured numerically like the ceiling height in meters and the distance between panels in meters.

The main purpose of the present paper is to advance in knowledge of the exploration and appropriation of the underground environment in the Palaeolithic, studying the accessibility to decorated sectors in caverns. A methodology is needed to compare those spaces in an objective and precise way. Its application to different decorated caves would allow us to infer the profile of the artists and the people related to graphic activities throughout the Upper Palaeolithic.

2. Methodology

Human transit in the endokarst is conditioned by a series of factors that, generally, imply more or less difficulty. That is to say, the effort expended travelling 100 m inside a cave with continuously narrow passages and vertical shafts, or in a cave with wide passages and high ceilings, is notably different. To give two examples, we can compare the exertion required to reach the "*galerie aux peintures*" in the cave of Etxeberri (Garate and Bourrillon 2019) at a distance of 150 m from the entrance, with the effort involved in reaching the "*salon noir*" in Niaux (Clottes 2010) 800 m from the entrance. Despite the occasional obstacles and a longer distance in the second case, access is much more difficult and dangerous in the first cave (shafts, cornices, ramps, etc.). But by how much?

Some of these difficulties are related to circumstances that are impossible to measure and determine: the physical condition of the people who transit the cave, their sense of orientation, their experience moving underground, the particular (seasonal) conditions of the cavern (wet/dry), etc. but also psychosocial constraints (e.g. a cultural prohibition, etc.) (Llobera 2000).

However, the morphology of a particular area in a cave is a common and measurable factor. The size of the passages or the inclination of the floor will be the same for all the individuals who go through the cave. These are always present, so they constitute a background on which the rest of the factors operate (Llobera 2000). Through empirical observations and experimental archaeology, we can estimate the cost of movements in the underground landscape.

2.1. *Measuring the cost of movements in caves during the Upper Palaeolithic*

Our method to find a way to measure cost of transit in caves consists of two essential methodological phases (a more detailed explanation can be consulted in Supplementary material S1). Firstly, experimentation, which must be controlled, replicable, demonstrable and follow a specific experimental programme (Baena and Terradas 2005; Baena 2013), and secondly an accurate analysis of data using standardized statistics to test the validity of the empirical approach. If empirical data display significance under the appropriate statistical formula, the research hypothesis is supported (Kleinbaum et al., 2002; Cardot and Sarda 2011).

Experimentation was designed to measure two parameters of cost (travel-rate and heart-rate) of individuals while they were travelling through some underground circuits. The former (measured in meters per second and then divided by 1) is used to measure the effect of topographical features like slope or roughness in open air surfaces (Campbell et al. 2017, 2019). Heart rate has often been employed for effort-measurements, but never in caves (Achten and Jeukendrup 2003; Luft et al., 2009). The evaluated topographic features of the caves were the size of the galleries (measured by height and width in meters) and the slope (in degrees), since it was evident that they affect in the method of displacement used (walking, crawling, climbing, etc.). Height of the passage is the distance (with 90° verticality) between the ground and the ceiling. The width is the horizontal (0°) distance between both walls.

The sample was formed by 21 volunteer participants selected from a group accustomed to working or frequenting caves to minimise psychological effects caused by lack of knowledge of underground environments or fear of the dark. It included people with different physical and sports skills, coming from different disciplines (cavers, archaeologist, biologist and geologist) and different levels of experience in caving. The formal characteristics of the population (age, weight and height) were analysed individually by Shapiro-Wilk normality tests (Royston 1982a, 1982b, 1995) with the R statistical packet (R Core Team, 2018), obtaining acceptable results. The sexes were represented equally, and the median and mean stature were similar to the average human stature during the European Late Upper Palaeolithic (Holt 2003). Despite the fact that these inferences must be taken with caution, owing to the absence and low representativeness of anthropological remains in these chronologies (LUP), we believe that they serve to establish valid criteria when estimating the cost of transit in caves, as shown by recent comparisons with ancient DNA (Cox et al., 2019). However, despite the indisputable frequentation and decoration of caves by children or small people, as evidenced by footprints discovered in such sites as Tuc d'Audoubert, Fontanet, Niaux and Pech-Merle (Bégouën et al., 2009; Pastoors et al., 2015; Ledoux et al., 2018), Chauvet (Garcia 2005) and Bàsura (Citton et al., 2017), in addition to painted hand stencils as in Fuente del Salín (Moure et al., 1984), these age ranges were not included in the experimentation to avoid possible damage or accidents to minors.

The experiment took place in Lamiñak cave-system (Berriatua, Northern Spain), only 300 m from the decorated cave of Atxurra. It is 4.7 km-long cave on several levels (GEV 1985) with a wide range of morphologies, very similar to Atxurra. Two sub-horizontal circuits were planned in a deep zone without natural lighting, on two overlapping cave levels, connected by a 7-m vertical chimney. We use also this last natural obstacle, in addition with a sub-vertical passage, to evaluate the effect of climbs. The upper circuit has a floor with a changing slope, while the ceiling constantly increases and decreases in height; it ends in a narrow 24 cm-high crawlway to a small chamber. The lower route has a more stable sloping floor and high ceilings. In these circuits, an attempt was made to summarize all the possible scenarios known in caves decorated with Palaeolithic art, as well as different types of movement (crawling, walking, climbing and traversing). The experimentation minimized the environmental and biological impact, in a cave with no known archaeological remains.

To perform the tests, the individuals wore neoprene socks to imitate prehistoric soft footwear, or went barefoot, as estimated in recent studies about footprints in prehistoric caves (Ledoux et al., 2018). They also carried an electric light in the form of a torch, imitating the use of torches by prehistoric societies inside caves, which meant that one hand was unavailable for helping the subterranean progression. Their weight and light intensity were similar to experimental prehistoric torches (Medina-Alcaide 2020). It was interesting to observe how the maximum achievable speed was greatly conditioned by the lighting: in the widest and most comfortable places, where it would be possible to move faster, it was limited to an average of 1.23 m per second by the smaller radius of the light. Other factors such as diet were not included in our analysis, despite the fact that there are proposals that take them into account to create algorithms (Van Leusen 1999).

All the data were statistically analysed in R. Normality tests were applied individually to the observations (both travel rate and heart rate) to rule out observations that could contain errors. Subsequently, the observations were normalized for a joint analysis of the data from which a multiple linear regression could be obtained (Casella et al., 2013). The following conclusions were reached from the preliminary analysis about the crawling and walking movements: the variables that have a greater linear relationship with travel rate are: height of the passage (r = −0.9), and slope (r = −0.276). Heart rate and the other variables are also correlated negatively, but more weakly, so it was discarded in the following experimentations (Fig. 1).

In a first multiple regression, it was observed that despite having a high coefficient of determination (0.9284), only the variable height of the passage was significant to explain the increase in travel rates. The explanatory variables slope and width did not offer a significant behaviour (Faraway 2014; Krzywinski and Altman 2015), perhaps due to the characteristics of the chosen galleries to make the experimentations. A new regression for walking and crawling was performed only with the variable height of the passages. This second regression has a lower R2 (0.8109), but it remains being hight and the p-value of the model is more significant that the precedent (0.005684), so it can be accepted that the model is not random, at least one of the partial regression coefficients is different from 0. Besides, the variable and the intercept are significant, with a high confidence level (0.99).

This process was repeated with the results of the circuits in which vertical movements were used (climbing or displacement by traversing, or applying opposite forces in both walls). The variable slope obtained a quasi-perfect negative linear relationship with Travel rate are (r = −0.999) (Fig. 2). By the other hand, height of the passage or width have not significant correlation with Travel rate (0.162 and −0.0171). So, a single regression was drawn using slope and obtaining a high R2 (0.9978), capable of explaining 99.78% of the variability observed in

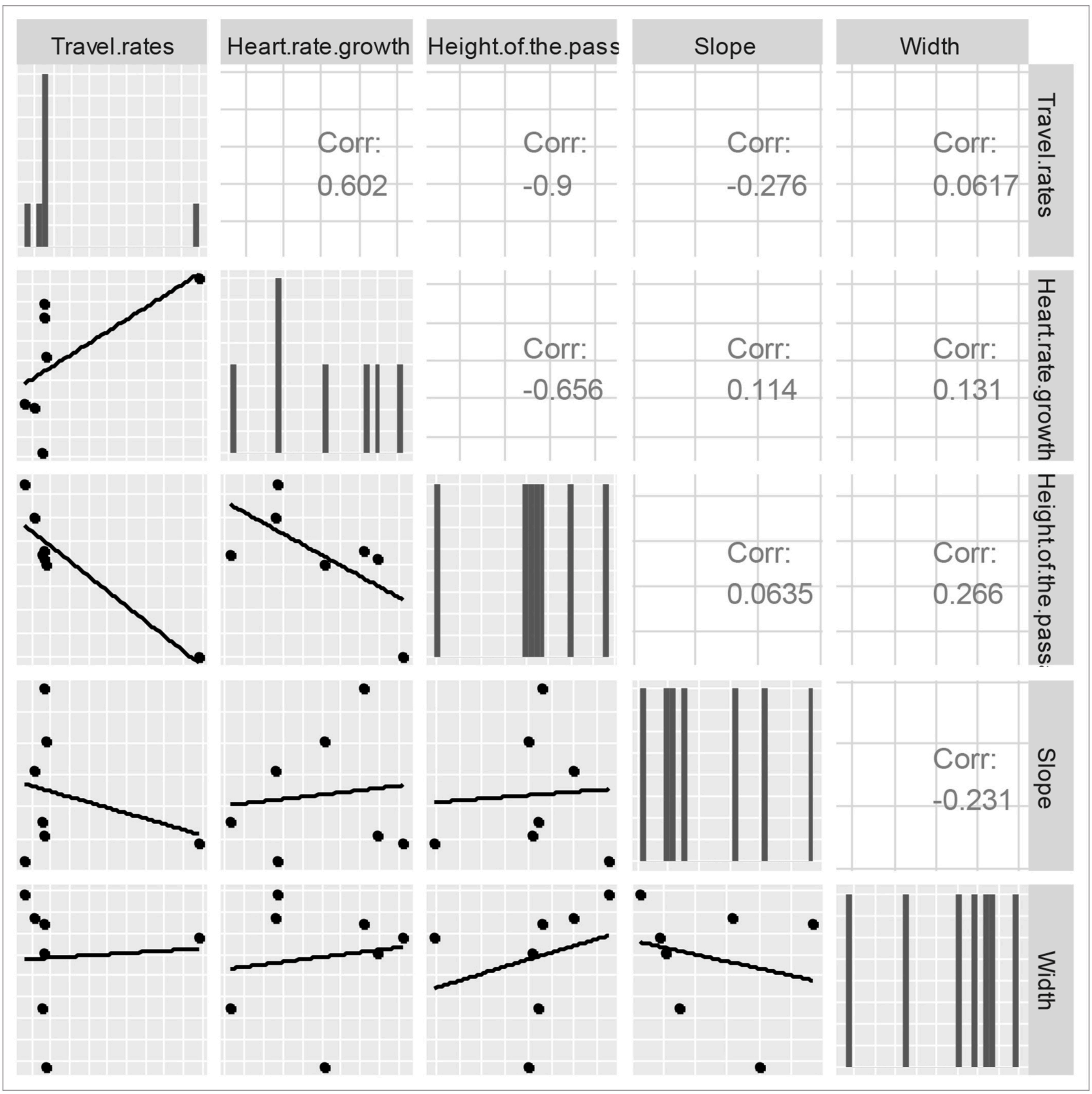

Fig. 1. Correlation between variables in crawling and walking movements.

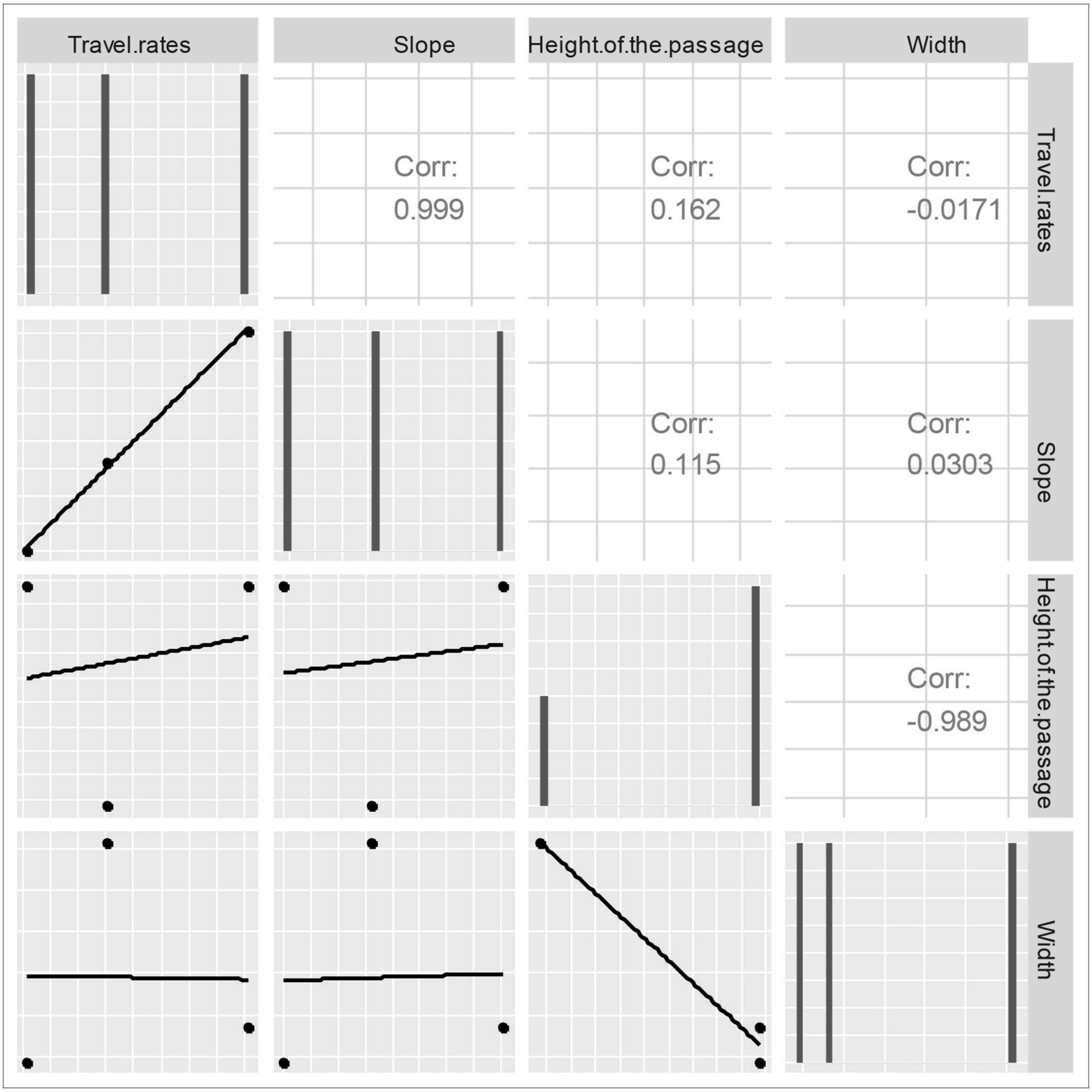

Fig. 2. Correlation between variables in climbing and traversing movements.

travel rates. The p-value of the model is significant (0.03014). Besides, the variable and the intercept are significant, with a high confidence level (0.95).

According to our observations, the boundary between walking and crawling is very fuzzy and is conditioned by the stature of the individual who transits a passage with variable height. That is, a single regression must be used to estimate the cost in these two types of movement. Also, the maximum slope supported by these types of movements is 45°. Values higher than 1.86 m (~11.607/6.217) will not affect the formula, so we will reconvert those values to 1.86 and eliminate those lower than 0.24 m (the average minimum boundary in the experimentation). However, the same is not the case with climbs and traversing movements, when the slope values are higher than 45° (~87.48216/1.95901). It was observed that not all individuals were able to overcome the vertical obstacles without human teamwork or technological aids. In any case, it was observed that the experience, strength and/or technique necessary to overcome these obstacles (chimneys, climbs) are considerably greater than those of travelling in horizontal passages (whatever the height of the passages). In those cases, a maximum time to overcome this obstacle was given to each participant (5 min), as the estimated time to prepare the aid. If they couldn't it, this maximum time was taken as reference to make the regression. The obtained formulas are the following:

$$Travel.rates_{in\ slopes\ lower\ than\ 45^{\circ}} = 11.607 - (6.217 * Height\ of\ the\ passages)$$

$$Travel.rates_{in\ slopes\ greater\ than\ 45^{\circ}} = -87.48216 + (1.95901 * Slope)$$

Other tests were also performed in the regressions (Shapiro Wilk test and Breusch-Pagan test), obtaining optimal results. The sample size (21) was also validated by the minimum number of observations.

2.2. Recreate the geomorphology of the cave

By the study of the karst geomorphology (Ford and Williams 2007), it is possible to simulate the geomorphology of a cave during prehistory, identifying the spaces that have been modified from the time they were frequented in Prehistory to the present day (passages that have been altered by the growth of speleothems, collapsed areas, sediment movements, etc.). While the use of 3D technology is already known in underground Palaeolithic art research (e.g. Fritz and Tosello 2007; Lerma et al., 2010; Hoblea et al., 2014; Fritz et al., 2016b), it is very important to consider changes to the caves since their frequentation in Prehistory, and to approach different studies (accessibility, capacity, visibility, etc.) with a model as close as possible to the site that the prehistoric societies found at that time. Examples of the use of 3D to recreate the morphology of a cave are known in Chauvet (France) (Delannoy et al., 2010; Sadier 2013) or Lascaux (France) (Lacanette and Malaurent 2010).

Scanning a cave with a laser-scanner obtains a point cloud from which a three-dimensional model of the cave can be extracted, and introduced in ArcGIS®, to create different raster-files (Scott and Janikas 2010), following a defined procedure (Opitz and Nowlin 2012). In this part, we must create those 3D files with we will work later. A file for ceilings (named as “CeilingsMax.wrl”), a file for paleofloors (“GroundOK.wrl”) and a file for those Zs that would affect transit, and which, when located in an intermediate situation, have not been taken into account (“CeilingsMin.wrl”). We can made them using software like Meshlab® (to cut and work independently in areas of interest) or Blender® (e.g. with “sculpting mode” to reduce and cut out Holocene formations) (Fig. 3). For those zones where two passages coincide at the same point (for example in overlapping cave levels), we must do independent models for sector-analysis.

2.3. GIS in caves: analysing the accessibility

Geographical Information Systems (GIS) provide an exhaustive framework for research in landscape archaeology (creating optimal routes, difficulty maps, visibility, etc.) (e.g. Lake et al., 1998; Bell and Lock, 2000; Ogburn 2006; Howey, 2007, 2011; Llobera 2011; Llobera et al., 2011; Gustas and Supernant, 2017; Opitz 2017; Wernke et al., 2017), while bearing in mind the limitations that other authors have indicated (Llobera 2012; Gillings 2017). Studies of accessibility, mobility and visibility using GIS are already known in open-air rock art (Hartley and Wolley Vawser 1998; Kohut 2018), including some punctual precedents known in closed and three-dimensionally complex sites (Boche et al., 2012; Ortega-Martínez 2012; Landeschi 2019).

Indeed, the GIS provide us with an adequate tool to calculate the morphologies of caves. The height of the galleries can be calculated by subtracting the Z’s from the ceilings and floors, the slope between the cells of a raster using software’s own algorithm, and by using trigonometry, the elevation gained between them. The cumulated cost will be calculated according to the raster cell size (in our case 5 cm^2), so this last value (gained elevation between cells) is used to count that distance in the vertical places (in a vertical jump of 2 m there would be space for 40 cells of 5 cm^2). However, other factors that can sometimes be important, such as the width of the galleries, cannot be calculated. Taking into account the regressions obtained through experimentation, it is possible to assess the accessibility to a certain point of a cave, including the decorated areas, at the time when they were decorated/viewed. For this we need to create two shapefiles: one from a point of origin (e.g. a paleoentry to the cave) called “Start.shp” and the other from a destination point (e.g. a graphical unit or GU, or evidence from the internal archaeological context or IAC) called “Destination.shp”. The processes to be carried out have been included in a python script for ArcGIS®, so that those interested can carry them out automatically (available in Supplementary Materials). The results obtained include the accessibility values, as well as the least cost path (LCP) and the estimated needed time to reach those points of the cave in the Upper Palaeolithic.

3. Materials: Atxurra Cave in northern Spain

The cave of Atxurra (Biscay, Northern Spain), a prehistoric site

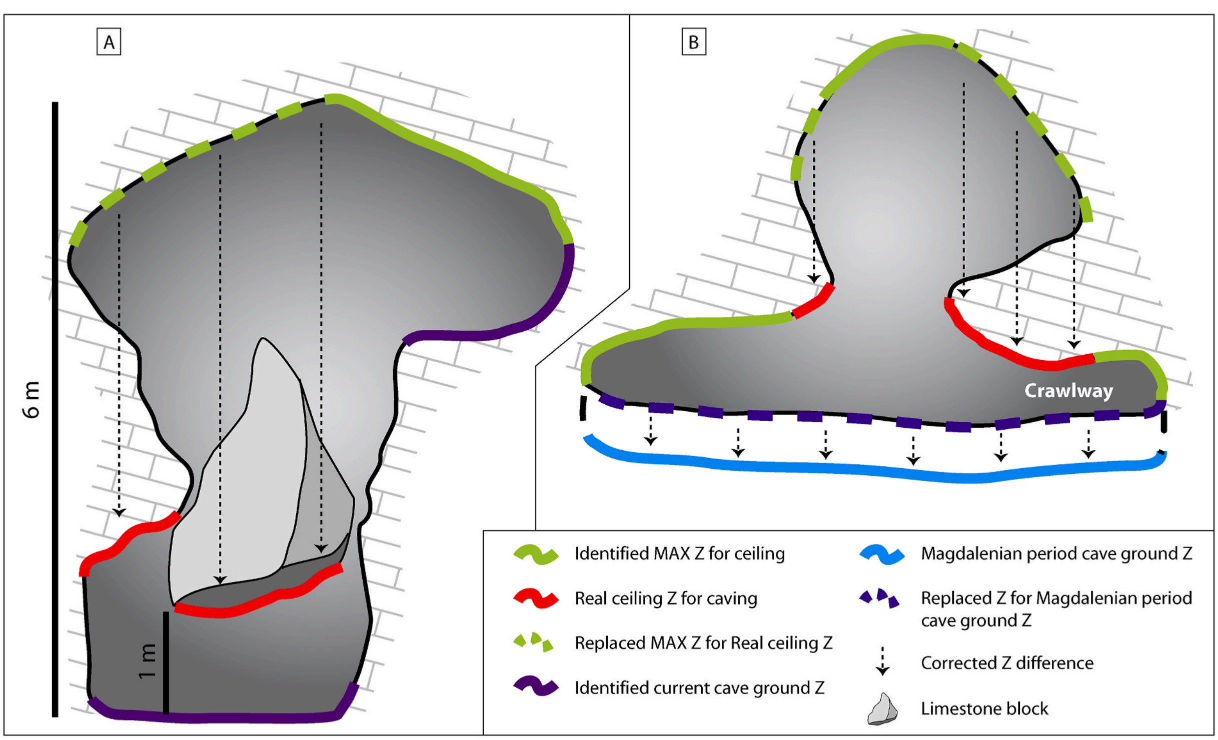

Fig. 3. Summary of the Z values that must be taken into account in the 3D models for accurate spatial analyses: A) those intermediate Z values that would act as ceilings, for example embedded blocks. B) modifications of the floor levels of the passage by subtracting/adding the centimeters corresponding to posterior regrowth/ erosion, to obtain the Palaeolithic floor level.

known since 1929 (Barandiarán 1961), was chosen to put this methodology into practice. In 2015, a rock art ensemble was discovered deep in the cave (at a distance of between 186 m and 366 m from the prehistoric access), with more than 113 engraved and painted animal depictions in Upper Magdalenian style (Garate et al. 2016, 2020a).

The cave system formed in Aptian-Albian reef limestone (Lower Cretaceous) (Fig. 4). It consists of two subhorizontal passages (cave levels) at different heights, the lower one called Armiña and the upper one called Atxurra. The entrances are located on the right bank of the Zulueta stream (tributary of the River Lea). The entrance of Atxurra was the natural entrance used by prehistoric societies to access the system and is currently 35 m above the stream. It leads to a small entrance hall where a Gravettian, Magdalenian and Neolithic-Chalcolithic occupation sequence has been identified (Barandiarán 1961; Rios-Garaizar et al. 2019a, 2020). There are two points of union between the levels, one of them a few meters from the upper-level occupation site (Atxurra) and the other at the end of the lower-level passage (under the point where the decorated sector begins).

The example of Atxurra is suitable for our purpose for a number of reasons:

- It is an ensemble of parietal art with complicated access. Between 2016 and 2020, in the course of exhaustive prospection and identification fieldwork, 257 graphic units (GUs) have been documented, usually located on a series of ledges that involve climbing or the use of speleological installations for safety.
- Archaeological remains are associated with the rock art. In the decorated areas, numerous scattered charcoal remains have been found and experimentation has shown that they come from prehistoric torches used for the lighting, in addition to a probable sandstone lamp and hearths. Also, some lithic tools (burins, blades, etc.) that may have been used to draw the parietal figures have been found next to some rock-art panels. The internal archaeological context (IAC) (Clottes 1993; Medina-Alcaide et al., 2018a) is fundamental to know the areas that were anthropized by the prehistoric groups, and the probable route they used to access the art. Specifically, the charcoal from the torches functions as markers of these areas, due to the gradual detachment of the residue of combustion, as proven in experimental studies (Galant et al., 2007; Moyes 2008).
- Once all the evidence in the cave (GUs and also elements of IAC) had been documented, they were georeferenced with a DistoX2 device, in addition to a tablet with Android system with Bluetooth™, and with TopoDroid® (Corvi 2015) application installed, following a proven recording method (Trimmis 2018).
- A geomorphological study of the cave has been carried out (Arriolabengoa et al. 2018, 2020). The first results have determined the processes of sedimentation and/or erosion that occurred in the underground system, before and after the entry of the Magdalenian artists.
- A three-dimensional model of the cave has been generated by the company Gim-Geomatics, SL using a terrestrial Laser Scanner 3D Faro® Photon 120. Approximately 59.6 million points have been obtained per scan, in 538 scan stations. As for the accuracy of the operation, the estimated error is 1 mm per 25 m, with 90% reflectance. This error has not been taken into account to make estimations, because it is imperceptible (we have used two decimal places, and the error affects the third one).

4. Results: accessibility analysis in Atxurra cave

The methodology described above has been applied in Atxurra Cave to assess the accessibility for all rock art and archaeological evidences distributed in 26 sectors (Table 1). As the cost has been measured in meters by second divided by one, the obtained cost value can be used to estimate the time needed in the Palaeolithic to reach the sectors. A more detailed description of the entire process, as well as the LCP to reach them, can be found in Supplementary Material (S3).

As a preliminary conclusion, it can be stated that a longer distance of transit through the cave does not imply greater difficulty or complexity, but a series of conditions (crawls, ledges, flowstones, ramps, etc.) related

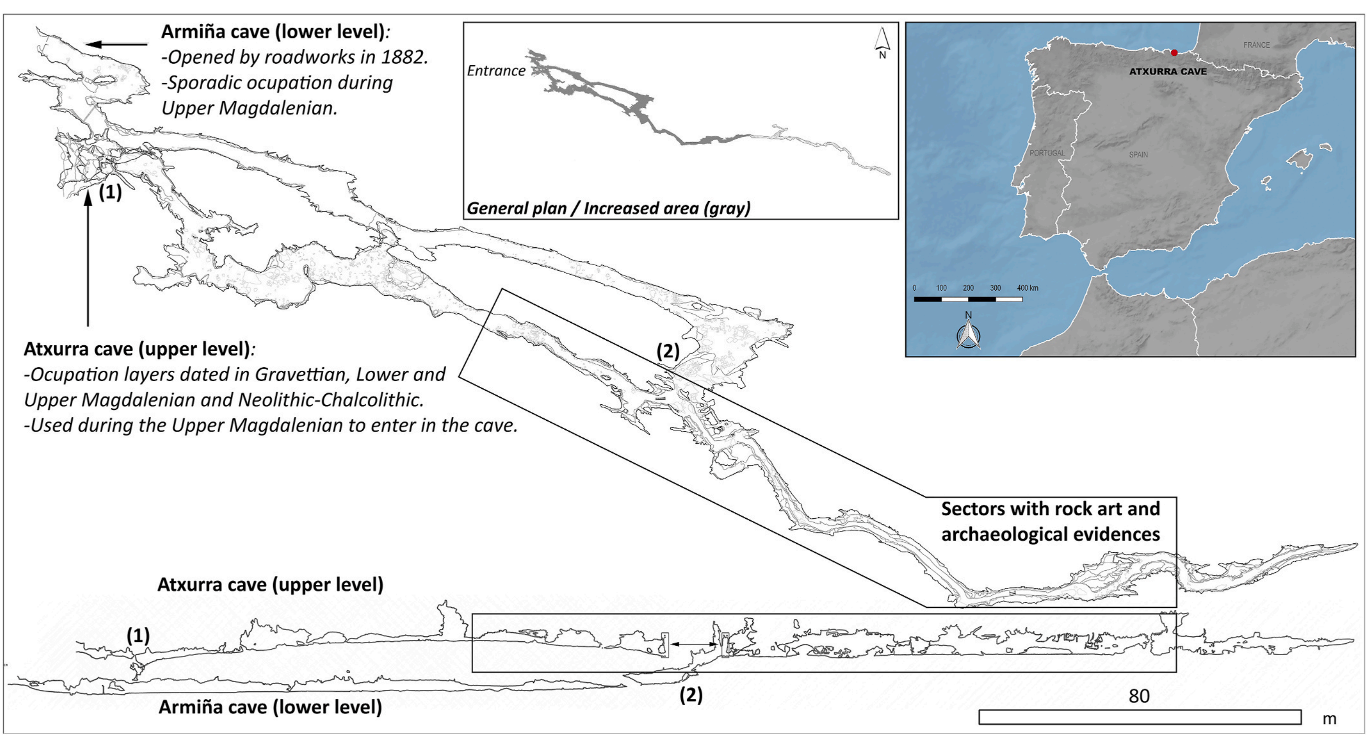

Fig. 4. Plan and elevation of Atxurra Cave generated from the scanned point cloud (Gim-Geomatics, SL), edited to show the entrances, the connections between the two levels ((1) and (2) in the map) and the sectors with rock art and archaeological evidences. The map of the Iberian Peninsula shows the location of Atxurra Cave (Source: https://www.juntadeandalucia.es/institutodeestadisticaycartografia/DERA/).

Table 1
Comparison of the accessibility (measured in cumulated cost value), the length of Least Cost Paths and the estimated needed time to reach each sector in the inner part of Atxurra cave during the Upper Palaeolithic with the number of GUs and IAC remains they contain.

Sectors	GUs	IAC	LCP length (in meters)	Cost	Needed time (in minutes)	Sectors	GUs	IAC	LCP length (in meters)	Cost	Needed time (in minutes)
Armiña		>100	72.94	104.6	3.19	F′	18	7	304.94	389.49	35.19
- A		2	141.45	62.59	4.54	H	3	2	308.02	456.09	37.30
A	1		192.66	75.89	5.58	G′	1	4	321.16	380.49	35.05
A′		5	220.30	68.86	8.01	G′ I Floor	10		296.75	266.58	36.21
B		1	202.49	121.14	6.60	I	1		320.69	375.03	39.30
C Floor	1		219.03	65.99	10.55	J Floor	3		361.63	268.22	34.20
C	32	36	235.79	198.84	12.26	J	89	>100	361.63	273.08	38.39
D Floor	2		235.56	141.16	10.70	I′		1	345.36	444.76	41.85
D	56	16	245.22	142.22	11.79	K		1	346.93	291.48	38.55
D′		11	252.17	140.9	16.60	L		1	361.35	269.41	39.22
F	1		261.26	159.72	18.02	J′ Floor	2		377.42	271.39	39.42
G	30	1	262.03	155.02	17.85	J′		2	383.13	403.24	41.66
E′	2		268.94	399.27	27.08	K′	1		379.81	270.22	39.47

to the morphology of the passage affect (complicate) progress through it. In addition, the results obtained in Atxurra seem to show that the artists' choice of panel was directly affected by the difficulty of transit (Fig. 5). The Upper Magdalenian groups in Atxurra chose panels with difficult access, although the options offered by the cave are much more extensive and less risky. However, the reason for this is unknown: a willingness to 'hide' this art? evidence of rites of passage? (Owens and Hayden 1997; Arias 2009). In some cases, it seems that the locations in high areas could have been related to more functional reasons, such as giving visual prominence to particular figures, as in Sector J (Intxaurbe et al., 2020). Regarding the estimated time to access the sectors, it increases for the zones that include constant vertical zones (passable by climbing or traversing), because not all potential cave visitors during the Upper Palaeolithic were able to overcome the vertical obstacles without assistance. On the other hand, experience, physical strength, or knowledge of the cave's topography would help to optimize the time required to access the deep areas.

5. Discussion: the utility of the method to assess accessibility in caves

This work proposes a new methodology to help answer certain questions related to the role that the space itself (the cave) could play in the artwork and, specifically, the impact of accessibility on Palaeolithic artistic activity and its significance. Accessibility studies can thus be added to research on other spatial parameters, like visibility or capacity (Villeneuve 2008; Ochoa and García-Díez 2018). Until now, there were real difficulties to compare the accessibility to two (or more) different zones of different caves, beyond qualify them qualitatively, classifying the zones in different groups (e.g. by type of movements used to reach them) (e.g. Pastoors and Weniger 2011; Ochoa and García-Díez 2018; Jouteau et al., 2019). Besides, there could exist some subjectivity when classifying in qualitative terms the accessibility to a sector. A researcher, maybe non-familiarized in subterranean progression, can characterize a space with a very different criterion from that of a person used to transit in caverns. In these cases, the opinion of one person cannot be compared with the other one.

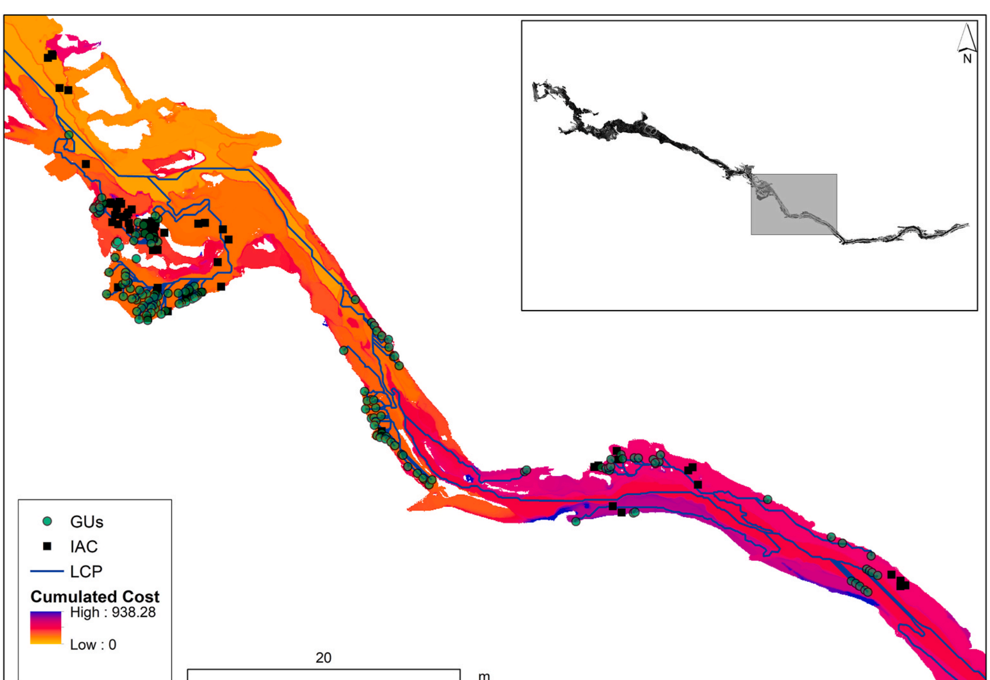

Fig. 5. Cumulated cost map and the Least Cost Paths to reach de GUs. The greater concentration of graphic activity is related with the high difficulty values (usually placed in the sides of the gallery). Note that the IAC remains are usually located around the estimated LCPs to GUs.

Although GIS is not designed *ex professo* for enclosed environments, we are able to 'introduce' these aspects by directly analysing the three-dimensional models (Landeschi 2019). As we have seen, a specific workflow has been developed to solve this problem. The method has been tested, and accurate results obtained, at least in Atxurra. The estimated LCP coincides mainly with the one used today to reach the decorated sectors. Geomorphological study pointed that there are not great changes in the deep parts of the cave since when it was frequented and decorated in the Upper Magdalenian (Arriolabengoa et al., 2020), so it is interesting to see that the path currently used to reach the panels (in our opinion the optimal) coincides which those estimated by GIS using our cost algorithms. Indeed, it is striking that the estimated LCP to reach IAC remains coincides also mainly with the one to reach GUs. It seems to confirm that the estimated LCP coincides also by the paleo-paths used in the Upper Magdalenian to access to the decorated sectors (Fig. 6).

Naturally, there are exceptions, that is, there are sectors with archaeological remains but no art, and therefore, they would lie outside the paths calculated by the GIS. It is interesting to highlight also the IAC remains in these 'off-route' sectors (S3), since they could be due to exploratory activities of Palaeolithic groups within the cave; or correspond to sectors that were decorated but their GUs have not been preserved (Rios-Garaizar et al., 2020).

Apart from obtaining accurate results, it is necessary to ask if this workflow is replicable by other researchers, in other scenarios. For it, we have summarized it in a python script for ArcGIS® (available in Supplementary Materials). Besides, it has been tested in the entire cave of the Atxurra, including overlapping galleries and vertical zones (where GIS could fail), in addition with a brief test in the cave Aitzbitarte IV with a paradigmatic case of rock art with very difficult access (Garate et al., 2020b). The former limitation has been solved by sectoring analysis, and the second test was also successful (S3). In the vertical zones, the script uses the own algorithm of ArcGIS® for *slopes* to, using trigonometry, obtain the elevation gained between cells, and by them calculate the effect of the costs algorithm also when the path is vertical (when the slope is bigger than 45°, and the movements are by climbing or transiting) (S2).

Finally, we can know other facts related with subterranean prehistoric transit. For example, the cost has been calculated in travel rates, so the results can be used to make estimations about the time used to reach the sectors during the Upper Palaeolithic. However, it is important to remember that the algorithms have been made taking also into account those participants who did not be able to overcome the vertical obstacles without aid, so those time for helping, or preparing is also counted. As some authors have pointed out (Rinella et al., 2019), "*caving, requires curiosity, perseverance and a great planning of cave exploration*". By other hand, is possible to estimate accurately what types of movements were used in the cave during the Palaeolithic frequentations, and by this, to question about the technological solutions probably used to help in the movement inside caves. The use of artificial lighting (essential in the deep sectors of a cave) (de Beaune 2000; Medina-Alcaide et al., 2015), or different tools, such as flint to break stalagmites and columns and to open blocked passages in Etxeberri (Rios-Garaizar et al., 2019b), or ropes to descend pits in Lascaux (Delluc and Delluc 1979), are known solutions that prehistoric groups employed to overcome the difficulties found in a cavern and caused by its morphology.

In any case, there could exist other possible cultural reasons to choose (or not) a particular route inside the cave or to decorate a zone (Domingo et al., 2020), so the results always must be taken in account with prudence and compared with other archaeological data (e.g. presence of charcoals, footprints, red stains, etc.) (Medina-Alcaide et al. 2018a, 2018b). Indeed, we are only considering one factor (the morphology of the subterranean landscape) to explain a very complex matter, because it constitutes the background on which the other factors operate. However, characterizing the different spaces morphologically can help us to conceive the technology or solution that could be used to cope with the adverse morphological features, as well as to determine other cultural or social features when choosing or transiting areas with different kinds of accessibility inside a prehistoric cave. For example, as observed in our experimentation, to estimate the costs of movement in caves, the last section of the access to Sector C in Atxurra confirms one (or several) of these statements: A) that the people who accessed it possessed great caving experience; B) that they used teamwork in the

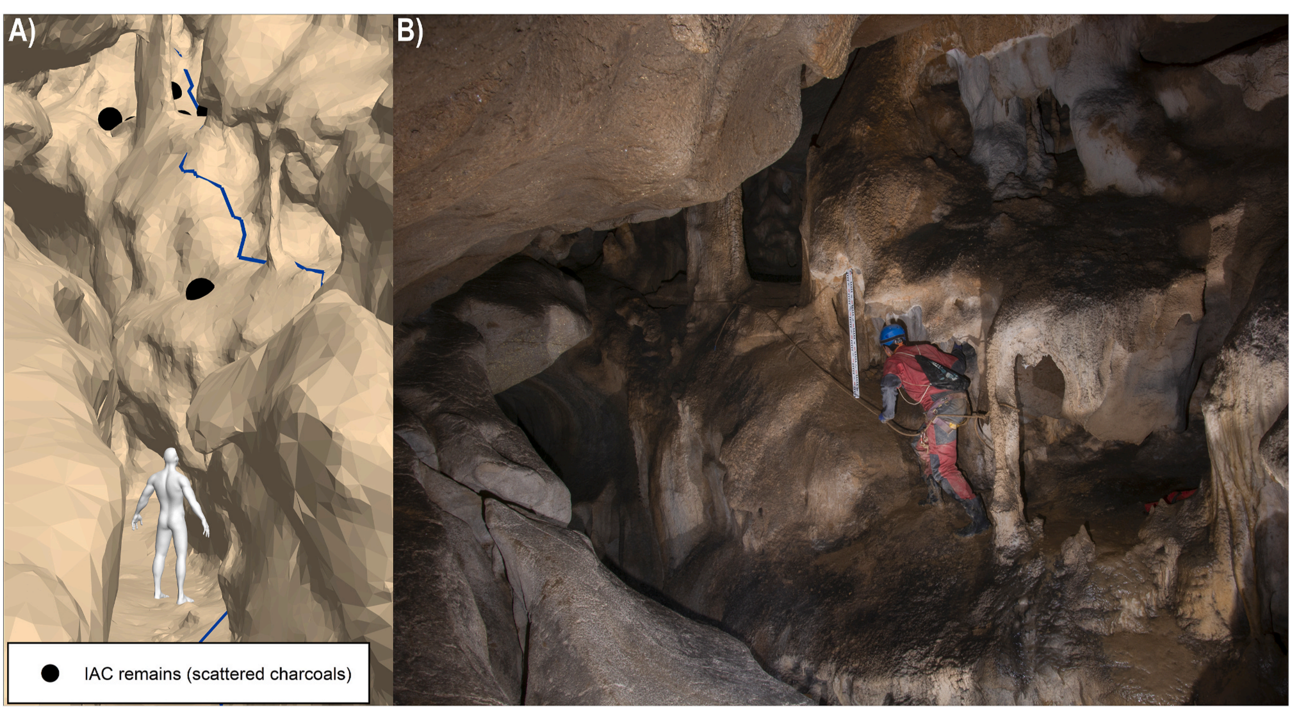

Fig. 6. Representation of the path to sector C: A) 3D visualization, extracted from ArcScene™ showing the estimated LCP (in blue). In addition, the presence of IAC remains over this path seems to confirm it was used by Palaeolithic groups. B) Photo showing the current access to Sector C, secured with a rope. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

access (practically essential); C) that they used certain technology to reach the sector. The morphology of the cave makes it difficult to transport, for example, wooden materials to construct scaffolding, and therefore the use of ropes seems more plausible. However, no evidence of such technology has been found in the cave, perhaps owing to the difficult conservation of this type of material (Aura et al., 2019).

6. Conclusions: a new approach to the prehistoric 'cavers'

This study has described a methodology capable of determining quantifiable parameters to assess the accessibility to different sectors in a cave with rock art (and/or archaeological remains), based on cave morphology and using 3D models in ArcGIS®. Prior to the analysis, geomorphologic studies must determine the changes that have occurred in the cave since the entry of prehistoric human groups. The effective application of the methodology in Atxurra cave confirms its utility. First, the cost of movements in caves was calculated through empirical observations and experimental archaeology, and precise statistical results were obtained. Subsequently, the accessibility to all the deep sectors in the cave were compared quantitatively (including all Graphic Units), obtaining accurate cost results and least-cost paths. Comparing spatial analysis results with each other, has allowed to infer the social or technological solutions, and the time employed by Palaeolithic societies to explore and frequent the cave system.

This methodology is employable in any cave that has been scanned three-dimensionally, and the workflow has been resumed in a python script to make it more accessible to other researchers. Therefore, its use in different decorated caverns will allow a common database to be created in the future, characterizing the results and permitting comparisons. We will be able to identify common patterns in the selection of the most inaccessible and deepest decorated and anthropized spaces, and analyse the characteristics of the graphic production and other activities carried out in them compared with spaces with easier access, in order to observe any differences in the patterns and envisage the possible solutions or mechanisms that Palaeolithic groups designed for the exploration of the caves. In conclusion, the application of this new methodology will achieve a better understanding of human behaviour inside the caves and the complexity of artistic activities, in order to unravel the symbolic purposes of Palaeolithic societies.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2020.105271.

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