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Potential and limitations of LiDAR altimetry in archaeological survey. Copper Age and Bronze Age settlements in southern Iberia

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1 | INTRODUCTION

The archaeological use of images and data obtained through devices carried on mobile platforms (such as airplanes and satellites) is already one century old. Today, aerial photography and remote sensing are routinely used to capture, process and analyse archaeological evidence present on the surface of the earth, which is reflected in a large body of literature—see Bewley (1999), Corsi et al. (2013), Palmer and Cox (1993), Piccarreta and Ceraudo (2000), Riley (1987) and Wilson (1982) for the former and Campana and Forte (2001), Lasaponara and Masini (2012), Limp (1989), Lyons (1981), Wiseman and El-Baz (2007) and Wheatley and Gillings (2013), for the latter.

In the last two decades, there has been a steady increase in the usage of altimetric analysis based on high-resolution techniques aimed at the detection of architectural elements both above ground and underground which are difficult to detect through conventional air photography and remote sensing methods. Prominent among those techniques is airborne laser scanning (ALS), which, like terrestrial laser scanning (TLS), allows for the detection and measurement of micro-topographies with a level of precision not attainable with conventional techniques of surveying and photogrammetric restitution (Challis et al., 2008; Chase et al., 2010; Doneus & Briese, 2006; Doneus & Kühteiber, 2013; Fernandez-Diaz et al., 2014; Fontana, 2022; Gallagher & Josephs, 2008; Harmon et al., 2006; Opitz, 2013; Opitz & Cowley, 2013; Risbøl, 2010; Risbøl & Gustavsen, 2018). As is well-known, this technology uses active LiDAR (light detection and ranging) sensors which emit a beam of polarized infrared light which is discretized in pulses in order to measure the distance between the sensor and the scanned object by the time difference between the pulse emission and the reception of its reflection (time of flight, TOF). This offers a value of the relative position of the object with regards the sensor, which in turn must be converted in absolute terrestrial coordinates within a geodesic system through an accurate measurement of the position, altitude, orientation and sensor speed by means of a global navigation satellite system (GNSS) with differential correction and an inertial measurement unit (IMU). When LiDAR sensors are fixed on airplanes, decimetric levels of accuracy are achieved, which may turn centimetric on helicopters or drones. The final result is a three-dimensional scatter of points which may be treated through digital 3D-modelling applications to create precise altimetric models, using both the first returns to produce a digital surface model (DSM) or the ground returns (filtered) to produce a digital terrain model (DTM) (Opitz, 2013).

The application of ALS technology to extensive archaeological reconnaissance is fairly recent. Over the last decade, LiDAR has proven extremely useful, particularly in densely forested regions of northern Europe, the American continent and Southeast Asia, although its usage in Mediterranean environments is still limited. After an initial phase of testing and calibration, highly innovative and even ground-breaking results have been achieved—see, for example, Barnes (2003), Doneus and Briese (2006), Doneus (2013), Harmon et al. (2006), Challis et al. (2008), Chase et al. (2010), Risbøl (2010), Crutchley (2013), Evans (2016), Canuto et al. (2018), Historic England (2018), Guyot et al. (2021), and Prümers et al. (2022).

In Spain, public, freely accessible and updated altimetric data are issued periodically since 2014, which has fostered a variety of uses in a number of disciplines, including Archaeology. The first archaeological applications of Spanish LiDAR survey data have appeared over the last 5 years, including case studies centred on Neolithic monuments, Iron Age cities and Roman camps—see Cerrillo-Cuenca and López López (2020) for a synthesis. The first of them examined an area of the Portuguese Alentejo region and Spanish Extremadura with known fortified sites and ditched enclosures, using 1 m resolution DTM from the LiDAR datasets obtained through the facilities of the Spanish National Geographic Institute (IGN in its Spanish acronym) (Cerrillo-Cuenca & Bueno Ramírez, 2019). The same IGN data were used to map the topography of Iron Age, Ancient and Medieval Cordoba (Monterroso-Checa et al., 2021), the amphitheatre of the Roman city of Torreparedones, as well as to suggest a new location for the Phoenician temple of Melkart (Hercules) in San Fernando, Cádiz, combining the laser altimetry with sonar bathymetry produced by the Spanish Oceanography Institute (Monterroso-Checa, 2017, 2019, 2021). Other very recent examples also include the reconnaisance of 135 Iron Age 'castros' (hillforts) in Galicia, including 25 previously unknown ones, with buried features, ditches, pathways, field boundaries and levelled defensive elements (Parcero-Oubiña, 2021), also a fresh cartography of the pre-Roman 'castro' at Irueña, Salamanca, combining surface surveys with LiDAR and GIS technology (Berrocal-Rangel et al., 2017) as well as a study of the Roman military presence in the northern fringe of the Duero basin, where 66 new archaeological sites were discovered thanks to the combined use of different remote sensing techniques and open access geospatial datasets, mainly aerial photography, satellite imagery and airborne LiDAR (Menéndez Blanco et al., 2020). Recent papers have looked into the possibilities of aerial LiDAR for the detection of megalithic mounds in Galicia (NW Spain) (Carrero-Pazos et al., 2014; Carrero-Pazos & Vilas Estévez, 2016). A very recent line of work looks at the development of algorithms for the automatic detection of archaeologically relevant micro-topographies through data mining and artificial intelligence, which has led to the successful location of a great number of megalithic mounds (Berganzo-Besga et al., 2021; Cerrillo-Cuenca, 2016).

Thus, while Spanish LiDAR survey data have been used to explore a relatively wide range of archaeological sites and features, including megalithic mounds, Phoenician temples, pre-Roman towns and Roman military camps, to this date, no attempt has been made to examine one of the most powerful 'segments' of Iberian Late Prehistory, namely, Copper Age (c. 3200–2200 BCE) and Bronze Age (c. 2200–850 BCE) settlements. The general aim of this paper is to test to what extent the resolution of the LiDAR data (in this case, the public data available for Spain) and the accuracy of the existing algorithms allow for identifications and characterizations of specific features and architectural elements found at settlements dating to the Copper Age (CA) and Bronze Age (BA). As will be explained below, not only there is a wealth of such sites awaiting examination but also the results obtained by us suggest that much can be gained from the use of LiDAR data in order to build a scientific understanding of them.

2 | CASE STUDY

Late prehistoric settlements with major stone-walled features are a pervasive phenomenon across most of the southern half of Iberia. In its early stages, starting c. 3000–2900 BCE, this was linked to the gradual sedentarisation of Late Neolithic communities coupled with a reduction of residential mobility, both of which were the result of demographic growth and economic intensification, allowing a greater accumulation of staple surplus. At various southern Iberian locations, 'fortified' or 'walled' sites have been interpreted as resulting from either defensive needs or monumentalisation practices (García Sanjuán & Murillo-Barroso, 2013; Gonçalves et al., 2013: 35; Jorge, 2003; Mataloto & Boaventura, 2009: 59). At an advanced stage, beginning c. 2200 BCE (Early BA), this phenomenon resulted in nucleated and well-defended settlements located on inaccessible hilltops, which also demanded the construction of large terraces capable of providing horizontal space to live on.

Thus, CA and BA settlements presenting major stone-walled features have been identified across much of southern Iberia (see distribution in the map shown in Figure 1). In the Spanish Southwest, they are common in the provinces of Huelva, where sites such as Cabezo de los Vientos, Cabezo Juré, El Trastejón and La Papúa have been excavated (García Sanjuán et al., 2011; Hurtado Pérez, García Sanjuán, & Hunt Ortiz, 2011; Nocete Calvo et al., 2004; Pérez Macías et al., 2019; Sánchez Díaz & Hunt Ortiz, 2021), as well as in Badajoz, where San Blas, La Pijotilla, Palacio Quemado, Los Cortinales and Castillo de Alange have been explored (Enríquez Navascues, 1990; Hurtado Pérez & Hunt Ortiz, 1999; Pavón Soldevila & Duque Espino, 2014). On the Portuguese side of the border, settlements located along the basins of the rivers Guadiana and Tagus, such as Santa Justa, Vila Nova de São Pedro, Leceia and Zambujal have been excavated over several decades (Cardoso, 1997).

In the Spanish Southeast, numerous CA and BA settlements showing major stone architecture have been excavated since the first explorations by Luis and Henry Siret in the late 19th century (Siret & Siret, 1890). Of course, they would be too numerous to list here. Although some settlements with major stone architecture flourished already in the CA, notably Los Millares, they became much more frequent and more impressive within the so-called 'Argaric' culture of the Early BA (c. 2200–1550 BCE)—see Chapman, 1990; Aranda Jiménez et al., 2015 for good syntheses in English. In the provinces of Jaén and Granada, excavated Argaric sites (not always well-published) include Peñalosa, Castellón Alto, Terrera del Reloj, Cerro de la Virgen and Cuesta del Negro (García Huerta & Morales Hervás, 2004). In the province of Almería, several major BA settlements located on hilltops and provided with very substantial stone-walled civil and defensive architecture were excavated, including the eponymous site of El Argar and others such as Fuente Álamo, El Oficio, Fuente Vermeja, Lugarico Viejo, El Picacho and Gatas (Gilman & Thornes, 1985). At these sites, the steep slopes were levelled by means of terraces while hilltops were often surrounded by an acropolis, sometimes including cisterns and other major infrastructures (Molina González & Cámara Serrano, 2004). Numerous Argaric BA settlements have also been excavated in the neighbouring Murcia province, including Placica de Caravaca, Covaticas, Cerro del Cuchillo, La Morra del Moro and Ifre (Eiroa, 2004), as well as, more recently, La Bastida and La Almoloya. With more than 4 ha and several levels of stepped terraces on which houses of areas between 10 and 70 m^2 were built, La Bastida is one of the largest BA settlements in the Spanish Southeast. On its perimeter, which is protected on three sides by steep cliffs, stands out a

FIGURE 1 Main Copper Age and Bronze Age settlements known in Iberia. Base map: © Instituto de Estadística y Cartografía de Andalucía [Colour figure can be viewed at wileyonlinelibrary.com]

defensive wall that could have stretched over 300 m, negotiating steep slopes of up to 40%. The excavated sector of this wall is 3 m wide, with bastions that project up to 3.50 m from its external face and are separated between 2.80 and 4.70 m. Considering the volume of collapsed materials, the original height of this wall would have been 5 m. At the lowest end of this wall, there is a 'covering gate' flanked by two 3 m wide forts, which make up a narrow 1.5 m wide corridor (Lull et al., 2014).

Further north, in La Mancha (the southern sector of the Spanish Central Plateau), dozens of BA settlements with major stone architecture have been described (Ruiz Taboada, 1997; Fernández-Posse et al., 2007; etc.) grouped in various types referred to in the literature as 'motillas' (such as Las Cañas, Los Romeros, El Retamar, El Acequión and El Azuer), 'morras' and 'castillejos' (El Quintanar, La Encantada, El Acebuchal, Los Dornajos, El Recuenco, Las Alberquillas and El Romeral). The same applies to the so-called 'Valencian BA', in the central sector of the Spanish Mediterranean coast (Tarradell, 1961), as can be seen in San Antón de Orihuela, Callosa de Segura, Lloma de Betxí, Tabaiá, Muntanya Assolada and Terlinques (Pedro Michó & Martí Oliver, 2004). Altogether, although these settlements share underlying locational preferences seen across southern Iberia, they are considerably smaller than those found in the southwest and the southeast, while stone-made civil or defensive architecture appears much less frequently and at a smaller scale, which sets them apart from the patterns seen in the Argaric area or the Sierra Morena region.

Given that, throughout southern Iberia, settlements dating to third and second millennia often show well-defined topographic features, caused by the large-scale stone architecture that was intrinsic to them, this paper departs from the assumption that LiDAR altimetry can contribute to a more precise planimetry of their morphology and features. The application of high-resolution LIDAR altimetry is aimed at examining the potential and limitations of the technology for future archaeological research and management. Strictly, the aim is not to assess the ability of high-resolution LIDAR altimetry to identify or locate 'new' archaeological sites, as this ability has been sufficiently demonstrated over the last 20 years (as briefly discussed above). Instead, the aim is to test to what extent it is possible to identify and characterize specific features and architectural elements with a matching or superior quality to that already achieved by other means, such as, principally, fieldwalking or air photography (obviously, LiDAR cannot match the level of precision attained by archaeological excavation through means such as hand drawing or photogrammetry).

With this aim in mind, a case study has been selected for which knowledge based on previous fieldwork, including fieldwalking and excavation, is available. This involves a series of CA and BA settlements located in the Sierra Morena highlands of southwestern Spain (Figure 2). Between the late 1980s and early 1990s, the University of Sevilla developed a research project across this region (northern provinces of Huelva and Sevilla). As part of said project, several survey seasons were undertaken which led to the discovery and characterization of multiple new settlements, two of which, namely, La Papúa II and El Trastejón, were also excavated in 1988, 1990 and 1994 (García Sanjuán, 1999; Hurtado Pérez, García Sanjuán, & Hunt Ortiz, 2011; Hurtado Pérez, García Sanjuán, Mondéjar Fernández de Quincoces, & Romero Bomba, 2011; Hurtado Pérez, Romero Bomba, & Rivera Jiménez, 2011; García Sanjuán et al., 2011). The fieldwork that led to the original data capture was executed by the same team (University of Sevilla) using the same criteria and methods, and therefore, there was a substantial unity in the quality and intensity of the field surveys that led to the discovery of the sites. Up to 36 of these settlements, for which previous documentation exists in the form of plans, photographs and written descriptions, have been selected in order to test to what extent can LiDAR altimetry improve and expand previously existing records.

Specifically, the potential and limitations of LiDAR to establish parameters such a site size, perimeter and major associated stone-built architectural features, including defensive walls with gates, bastions and towers, terraces, dwellings and even pathways, streets and roads, will be examined. The underlying assumption is that if high-resolution LiDAR can match or even surpass what was previously mapped on the basis of direct observation by fieldwalking, field topography and aerial photography, then the method can be safely used to detect and characterize new settlements in regions with analogous geographic settings for which no previous research is available. In principle, this has great potential both for research and management purposes, as it could lead to the creation of inventories of sites which may be legally protected on the basis of LiDAR-based surveys alone with (or even without) ulterior ground truthing.

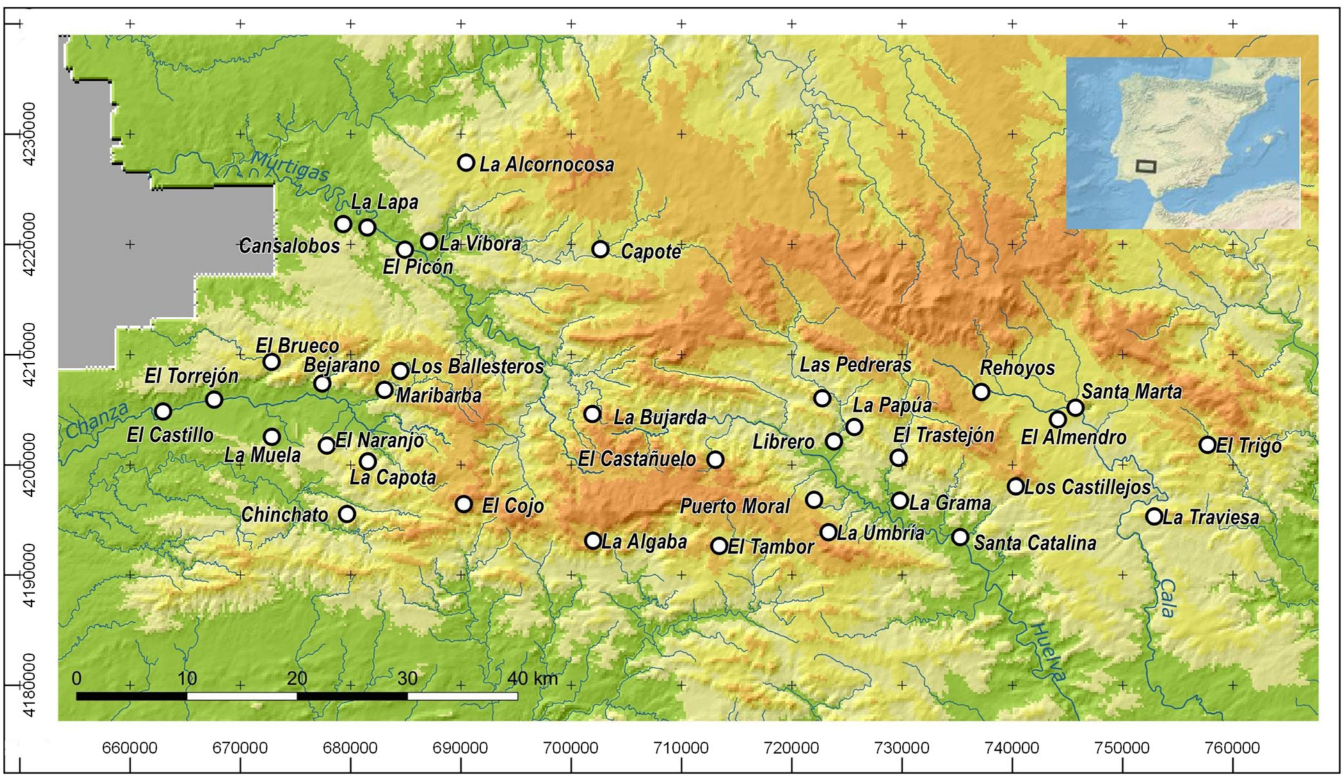

FIGURE 2 Distribution map of the sites included in this study. Base map: © LiDAR-PNOA 2014 CC-BY 4.0 scne.es. Coordinates: EPSG 25829 in metres [Colour figure can be viewed at wileyonlinelibrary.com]

3 | METHODS

The application of ALS technologies to archaeological survey has led to the consolidation of a new methodology with well-defined and well-tested phases, processes and parameters (Adamopoulos & Rinaudo, 2020; Lozić & Štular, 2021). The usual workflow includes the capture, processing, analysis, interpretation and representation of data. In turn, each of these phases incorporates specific processes, some obligatory and some optional (Figure 3). For this study, we used the LiDAR data captured by the Spanish IGN in 2014 with a density of 1 p/m^2, reduced to a 0.32 p/m^2 once ground-classified, rasterized into DTMs with a pixel size of 1 m using the open-source programme LASTools and visualized with relief visualization toolbox (RVT) and the 3D module of QGIS named Qgis2threejs to interpret archaeological structures.

The capture of altimetric information is normally made in the winter, in order to minimize the 'masking' effect caused by vegetation. Flight altitudes oscillate between 200 m for drone-based projects (UAVs), 650 m for helicopters and 3000 m for airplanes, with pulse emission frequencies between 45 and 500 kHz. With these altitude and frequency settings, data point densities normally ranging between 0.5 and 21 points per square metre are achieved, although there are major differences between official reconnaissance projects run by state agencies with multipurpose coverage (between 0.5 p/m^2 in Spain and 8 in the Netherlands, for example) and those tailor-made for archaeological purposes, which normally achieve 16 p/m^2

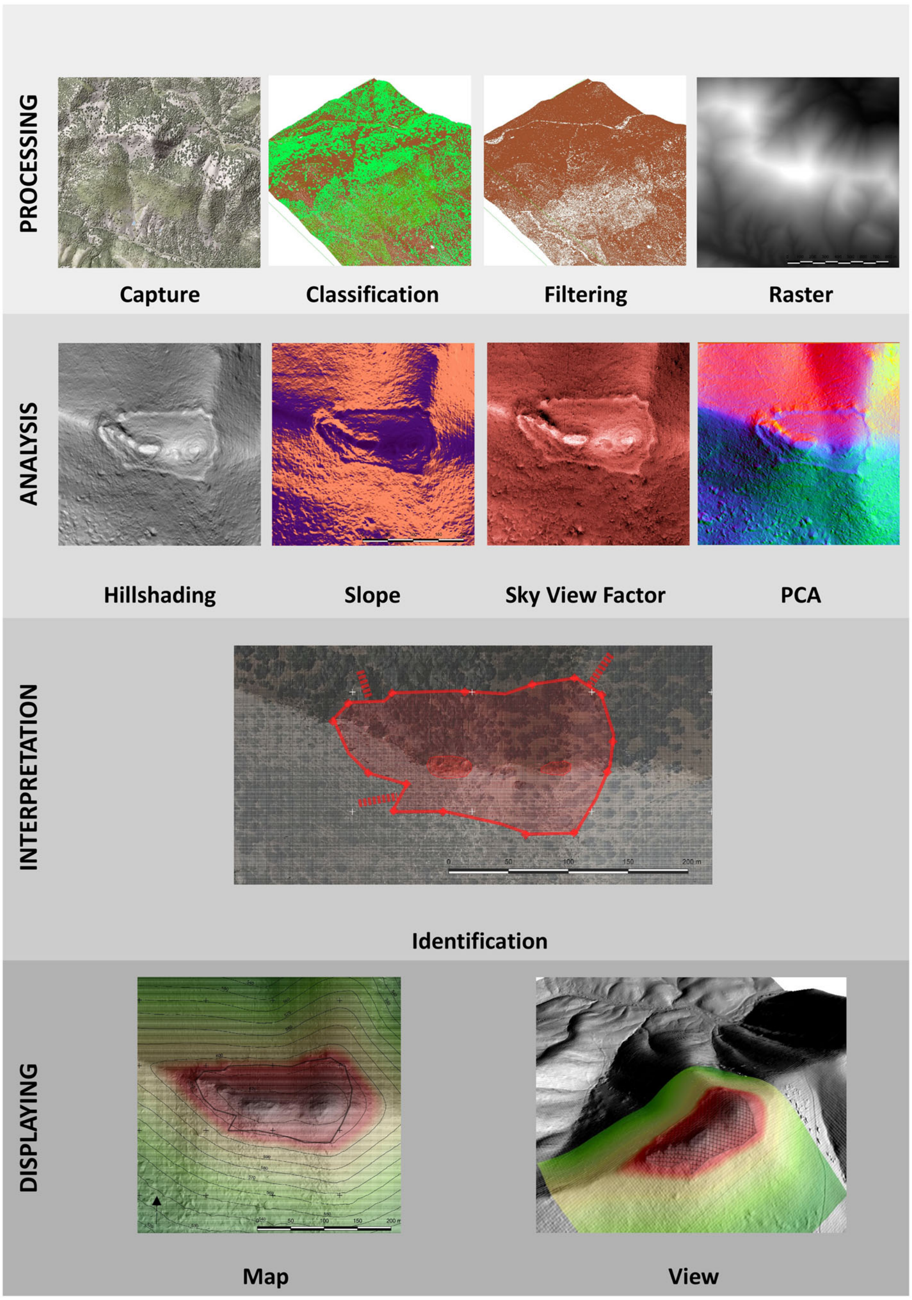

FIGURE 3 Usual workflow in an archaeological project with airborne laser scanning (ALS) [Colour figure can be viewed at wileyonlinelibrary.com]

(Table 1). On the other hand, altimetric precision is barely influenced by flight altitude, as with 650 m the root-mean-square error (RMSE) Z reaches 10 cm, whereas at 3000 m it reaches 20 cm, on account of the error induced by GNSS and IMU systems, which is bigger than that of the altimeter and independent from altitude. The field of view (FOV) is usually limited to a maximum of 50°, given that with higher angles, the probability of the beam hitting the ground is too low. Once the data point scatter is captured, it is subjected to a process that includes quality control, geometric correction, transformation of altimetric datum, georeferencing within a coordinate system, colour attribution on the basis of orthophotos, differentiation and classification of returns, organization in squares and compression into LAS or LAZ formats (Lorite Martínez et al., 2017).

In our case, a study area of 100 × 40 km was been defined for which LiDAR data were obtained from the Spanish National Centre of Geographic Information (CNIG in its Spanish acronym),[1] which supplies the LiDAR point coverages produced within the framework of the National Plan of Aerial Orthophotography (PNOA), with a 6-year periodicity and coverage for the whole country. CNIG supplies LAZ-format files with point scatters arranged by 2 × 2 km cells, automatically classified by FWF and coloured by RGB and infrared on the basis of 25 cm orthophotos. As well as being public and free, the CNIG licence of use incorporates a copyright cession which allows the reutilization of the data for any lawful purpose, with the only condition of recognizing and acknowledging the source of the data, as well as citing authorship. This is a product funded by the Spanish National Cartographic System, and recognition of copyright must be expressed as © LiDAR-PNOA 2014 CC-BY 4.0 scne.es.

The technical specifications of PNOA's ALS coverage set the parameters concerning flight, sensors, processes and final data which this new cartographic product must satisfy (IGN, 2014). According to these specifications, the point scatter must include orthometric altitudes over the EGM08 reference geoid, UTM projections in various zones, 0.5 p/m^2 point density—or 1.5 in the new series—and a minimum 40 cm RMSE Z altimetric precision, with 20 cm average. Other relevant specifications for archaeological use include 3000 m maximum flight altitude, 50° maximum angle, 45 kHz minimum scan frequency, ≤1.41 m point spacing, up to four returns per pulse with discrimination in vertical distance of at least 4 m, 8-bit radiometric resolution and global horizontal position lower than 30 cm RMSE X, Y (Lorite Martínez et al., 2017). These initial specifications, regarded as minimum standards, are basically satisfied within different regions of Spain. For western Sierra Morena, the 2014 coverage provides an even better quality. The usual resolution is in fact higher than 1 p/m^2 and in some cases above 2 p/m^2, which allows to derive raster LiDAR-based DTMs with 1 m resolution. In addition, the average distance between points is reduced to 0.99 m and sometimes even below 0.7 m. Table 2 shows the quality parameters of the LiDAR data processed as part of this study.

In order to achieve the phase of classification of returns, full-waveform (FWF) analysis of the reflected signal allows the decomposition of the various echoes that form it, assigning an altitude to each of the captured objects while at the same time differentiating first,

TABLE 1 Specifications of ALS flights used in archaeological projects

Zone	Spain	England	Norway	Netherlands	Hebrides	Brittany	Guatemala	Mexico	Cambodia
Source	IGN, (2014)	Crutchley (2013)	https://hoydedata.no/LaserInnsyn/	https://www.pdok.nl/	https://remotesensingdata.gov.scot/	Guyot et al. (2021)	Canuto et al. (2018)	Ringle et al. (2021)	Evans et al. (2013)
Pulses/m^2	0.5–1.5	4	2	8	16	14	15	21	16
DTM m	5–1	1	1	0,5	0,25	0,5	1	0,5	0,25
FOV °	50					26		28	45
RMSE Z m	0.20	0.15	0.10	0.05	0.15	0.10	0.10	0,10	0,15

Abbreviations: DTM, digital terrain model; FOV, field of view.

TABLE 2 Quality parameters of LiDAR data used in the 36 surveyed sites

	Area surveyed	Total points	Last returns	Ground points	Ground/ total	Ground/ vegetation	Angle max	Spacing	Points density	Ground density
Unit	m^2	n°	n°	n°	%	n°	°	m	p/m^2	p/m^2
Max	1 493 500	1 363 237	1 105 854	535 114	54.25	3.78	43	1.65	2.15	0.77
Min	109 744	71 617	71 617	15 977	12.78	0.40	12	0.68	0.37	0.12
Mean	538 145	575 401	483 206	174 568	30.33	1.32	25	0.99	1.07	0.32
Sum	19 373 216	20 714 422	17 395 433	6 284 433						

Abbreviation: LiDAR, light detection and ranging.

intermediate and last returns. Of these processes, the most archaeologically relevant is the classification of data points according to object type (Doneus et al., 2020), for which both return gap and intensity of the reflected signal are used. In the case of Spain, in order to differentiate between buildings and high vegetation, the vegetation coverage index (NDVI), calculated on the basis of infrared imagery, is used in addition. This classification process is automatized by means of algorithms connecting the position of each point with the nearest ones, although this involves a subsequent correction of errors that has to be done manually (Lorite Martínez et al., 2017).

Filtering of returns to obtain the altitude of the bare ground once buildings and vegetation have been removed can be an issue. Scarcity of soil returns caused by vegetation density and imprecision of classifications can become major limitations of LiDAR-based remote sensing. In the case of PNOA's LiDAR, which offers already classified returns, only 6.3 million out of 20.7 million points processed for this study corresponded to Class 2 (ground), while 4.7 million were assigned to vegetation. The rest, almost half, were not been classified and were assigned to Class 12 (overlay), Class 7 (noise) or Class 1 (unclassified), which causes half the potential resolution to be lost. In practice, this reduction to 30% of the points available to derive a DTM causes usable returns to have an average density of only 0.32 p/m^2, with peaks between 0.12 and 0.77 p/m^2. It is important to note that when the Class 2 (ground) point density fell below 0.25 p/m^2, it was not possible to identify archaeological features. On the other hand, when the point density was above 0.5 p/m^2, it was possible to identify terraces or walls in all cases.

Once processed, LiDAR data are available for downloading from national cartographic agencies, divided into squares which in Spain measure 2×2 km (by comparison, they measure 5×5 km in England) and converted into a DTM for their analysis, typically using ground-classified points in order to eliminate vegetation and/or buildings. In principle, it is sufficient to use type 2 (ground), but depending on the quality of the classification, some points labelled as 6 (building) may contain archaeological features, or some points identified as 3 (low vegetation) may be ground (Costa-García et al., 2017; Costa-García & Fonte, 2017). Depending on the density of returns at ground level, more or less precise DTMs can be achieved (Opitz & Cowley, 2013). In the case of PNOA's LiDAR, the usable returns had an average density of only 0.32 p/m^2, with peaks between 0.12 and 0.77 p/m^2, which allowed to derive LiDAR-based DTMs with 1 m resolution through interpolation if, instead of rasterizing altitude values through K-Nearest Neighbours Algorithm (KNN) algorithm, the DTM is derived from an intermediate tridimensional model in triangulated irregular network (TIN) (Štular et al., 2021). In our case, the open-source programme LASTools, integrated in package QGIS, was used to calculate the DTMs in the GeoTIFF format.

Starting from the DTM, the entire process of raster analysis can be achieved through map algebra. The detection of archaeological features is based on the analysis of relief variation details, for which algorithms automatizing form recognition are being developed but which still demand a visual interpretation (Verschoof-van der Vaart et al., 2020). Microtopography-enhancing methods range from simple hillshading (HS), to more complex techniques based on calculations of slope and aspect. Among the latter are algorithms normally used for archaeological survey such as sky view factor (SVF), openness, local relief model (LRM), principal components analysis (PCA), local dominance (LD), cumulative visibility (CV), multiscale integral invariants (MSII) or Laplacian-of-Gaussian (LoG) (Bennett et al., 2012). Especially, the red relief image maps (RRIM) visualization technique enhances the visibility of subtle features combining Slope, Hillshade and Differential Openness (Daxer, 2020). Thanks to work undertaken in the last decade, the parameters needed for each method are now more precise, including azimuth, elevation, filtering radius, number of directions or search distance (Kokalj & Hesse, 2017). In any case, for the identification of archaeological features, a combination of several of these techniques may be necessary, depending on factors such as feature size, slope of the terrain, land use or surface alterations (Costa-García & Fonte, 2017). In the case of the CA and BA settlements examined here, with a terraced relief, the most useful techniques were slope, SVF, PCA and RRIM, by means of software RVT and lidar visualization toolbox (LiVT) (Kokalj & Hesse, 2017). Table 3 shows the techniques, parameters and values used in this study for the visualization of settlements.

The interpretation of images, whether visual or automatic, is aimed at the identification, inventory and cartographic representation of archaeological features. In the case of terraces, a very useful algorithm for their automatic identification is the GRASS function *r.param.scale*, which measures the convexity in the direction of maximum slope (Arnau-Rosalén et al., 2018). Normally, a distinction is made between polygonal features such as enclosures, terraces, dwellings or burials; linear features, such as roads, canals or walls; and point

TABLE 3 Techniques, parameters and values used for the visualization of terraced settlements

Techniques	Parameters		Values
Hillshade	Azimuth		315° to 45°
	Elevation		30°
	Stretch		Linear, 2% cut-off
Slope	Unit		Degrees
	Stretch		Linear, 0° to 60°
Sky view factor	Search radius (pixels)		10
	Directions		16
	Stretch		Linear, 0.64 to 1
PCA of Hillshade	Components		3 (RGB)
	Elevation		25°
	Directions		16
	Stretch		Linear, 2% cut-off
Local relief model	Search radius (pixels)		25
	Stretch		Linear, −1 to 1 m
Positive openness	Search radius (pixels)		10
	Directions		16
	Stretch		Linear, 0.6 to 1
Visualization for archaeological topography	Sky View Factor	Stretch	Linear, 0.7 to 1
		Blend	Multiply
		Opacity	25
	Positive Openness	Stretch	Linear, 68 to 93
		Blend	Overlay
		Opacity	50
	Slope	Stretch	Linear, 0° to 50°
		Blend	Luminosity
		Opacity	50
	Analytical Hillshading	Stretch	Linear, 0 to 1
		Blend	Normal
		Opacity	100
Red relief image maps	Slope	Stretch	Linear, 0° to 50°
		Blend	Multiply (red)
		Opacity	80
	Differential Openness	Stretch	Linear, 1% cut-off
		Blend	Normal
		Opacity	100
Figure 7: Hypsographic maps	Elevation	Stretch	Linear, mean + − 1 s
		Blend	Multiply (green to red)
		Opacity	50
	Slope	Stretch	Linear, 0° to 50°
		Blend	Multiply
		Opacity	100

features (Mlekuž, 2013). In the interpretation of LiDAR data and aerial photographs, Historic England uses a classification according to relief morphology, distinguishing four types: structure, ditch, bank and slope. This process involves the conversion of the shapes seen on the images from their raster format into new vectorial entities, which may be stored in spatial databases and used in geographic information systems (GIS) (Gillings et al., 2020). The last phase of ALS projects includes the representation of the identified features based on the many possibilities offered by cartographic semiology. Normally, intuitive representations akin to natural vision are used, based on the shading of relief through low illumination, between 10° and 35° and 315° azimuth (Kokalj & Hesse, 2017). Other useful cartographic representations can be achieved through altimetric colours combined with slopes (Kokalj & Somrak, 2019). Given the potential of LiDAR data to create 3D virtual environments, one of the most recurrent ways to display and disseminate results is through perspective views, which may even be interactive when published in web environments (Popovic et al., 2017). In this study, both the interpretation phase and the mapping and 3D render phase were carried out using the open-source software QGIS 3.2.2 with SAGA 2.3.2 and GRASS 7.

There is no single computing package capable of handling the execution of all the processes described above in a fully integrated environment, although recently, the Open LiDAR Toolbox integrates an archaeology-specific LiDAR workflow into a unified interface, using GRASS, QGIS, LASTools and RVT libraries (Štular et al., 2021). Therefore, specific pieces of software must be used for each of those phases. The capture and treatment of raw data are linked to sensors and are usually achieved through licenced software such as Trimble MX or Leica LSS, a software tool for point-cloud generation and cleaning of raw LiDAR data. For all other processes, there are free open-source programmes, whether as plug-ins integrated in GIS or as independent applications. The classification of returns through FWF can be achieved with open-source software packages such as MCC-Lidar, Fusion or LASTools, although there are also commercial programmes, such as TerraSolid, VR Mesh or MARS. For point visualization, filtering, cutting, union, transformation or exportation, the most used programme is LASTools, which can be integrated in packages such as QGIS or ArcGIS, although there are other open-source programmes such as MeshLab, Geomagic XOS and FugroViewer. To convert an LAS file into a DTM raster file, the commercial software Surfer or the open-source Whitebox Geospatial Analysis Tools and LASTools are available, with exportation into different formats such as TIF, BIL, IMG, CSV or ASCII. For DTM analysis and exportation into image format, there is a number of raster GIS packages, such as SAGA and GRASS, but specific and valuable archaeology-oriented tools have been developed, as is the case with RVT and LiVT. The interpretation stage is the least automated of all, although it can be supported by generic GIS packages. Visualization through perspective-viewing and 3D visual environments, including web publication, can be achieved through both commercial (Geoweb3d) or open-source (Qgis2threejs) applications.

4 | RESULTS

The approach described above leads to a number of significant results concerning the usability of Spanish public LiDAR data to map CA and BA sites. Provided some conditions are met, such data can be used

TABLE 4 Comparison of architectural features detected by field work and by LiDAR

		Fieldwalking			LiDAR		
Name	Municipality	Chronology	Area (ha)	Features	Area (m^2)	Perimeter (m)	Features
La Papúa II	Arroyomolinos de León	BA	10	W/B/G	110,908	1747	W/B/G
La Papúa I	Arroyomolinos de León	BA	5	W/G	55,402	994	W
La Lapa	Encinasola	BA	0,1	T/W	42,836	984	T/W
El Trastejón	Zufre	BA	3	T/W/B/G	32,404	883	T/W/B/G
Atalaya del Trastejón	Zufre	BA	0,52	W	5,259	458	W
Castrejón de Capote	Higuera La Real	BA/IA	3	W/G	29,450	851	W/G
Las Pedreras	Cañaveral de León	BA	0,8	W	22,435	676	T/W/B/G
La Bujarda	La Nava	BA	1,4	T/W/B	18,175	703	T/W/B/G
Cerro del Cojo	Cortegana	CA	0,37	W	15,894	508	T/W/B
Los Rehoyos	Cala	CA/BA		T	13,308	484	T
Santa Catalina	Zufre	BA	1,1	T	12,168	471	W
Castillo	Aroche	BA	1	W	11,609	433	T
El Torrejón	Aroche	CA/IA	0,8	W	8,224	485	T/W/B/G
Los Castillejos	Santa Olalla del Cala	CA/IA	0,05	W	7,101	488	T/W/B
Cerro Librero	Corteconcepción	CA/BA	0,2	T	4,737	286	T
El Castañuelo	Aracena	BA/IA	1,1	W	4,300	293	T
La Muela	Aroche	CA/IA		W	3,290	251	T
Santa Marta III	Santa Olalla del Cala	BA		T	3,152	212	T
Santa Marta II	Santa Olalla del Cala	BA	0,7	T/W/B	3,089	224	T/W
Cerro del Almendro	Santa Olalla del Cala	CA	1	T/W	1,158	157	T

Abbreviations: CA, Copper Age; B, Bastions; BA, Bronze Age; G, Gates; IA, Iron Age; LiDAR, light detection and ranging; T, terraces; W, walls.

with a reasonably high level of success to produce plans of matching or superior quality to those obtained through fieldwork, leading to significant results concerning Intrasite microtopographic and architectural analysis, site size and settlement patterns. A full summary of results is shown in Table 4.

4.1 | Degree of success and masking factors

The first result to be noted is that the LiDAR-based approach to previously documented CA and BA settlements in the Sierra Morena range of southwest Spain has led to some remarkably precise 'surveys' and to the correct identification and mapping of several stone-made architectural features. In 20 out of the 36 selected settlements, the microtopographic analysis revealed walls, bastions, terraces, acropolises, possible embankments, gates and roads, whereas for the remaining 16 settlements, features previously identified on the ground were not detected in the laser altimetry, whether because of changes in the topography or because of insufficient data resolution. Thus, although in some cases, the LiDAR survey did not return any usable evidence to compare with the information previously gathered through fieldwork, it can be said that, overall, LiDAR data can achieve a reasonable degree of success in the study of CA and BA walled settlements.

There are two main reasons why LiDAR did not yield better results than previous fieldwork for a relatively high number of settlements: (a) the currently observable morphology of the sites (normally sitting on hilltops and hillsides) does not bear any traces of past reliefs; (b) the resolution of the available LiDAR data is insufficient (Figure 4). Regarding the first problem, in cases in which the topography has been heavily modified between the late 1990s and the present day by forestry management (e.g., tracks, fire breaks or terracing for tree plantations), agriculture (terracing for olive-tree cultivation), erosion or other factors, LiDAR data cannot detect CA and BA stone-made features. Examples of this abound in the western sector of the study area, around the Chanza and Múrtigas rivers, where intense forestry work has often altered the surface of archaeological sites. That is the case with sites such as Bejarano, Pico de Los Ballesteros, Cerro del Brueco, Huerto del Picón, El Tambor and Sierra de La Víbora. However, it is important to note that all of these settlements date to the CA and none to the BA. This is relevant, as the scale and extent of stone-walled features in the CA were consistently much lower than those of the BA. Therefore, the fact that LiDAR-based analysis did not reveal any architectural elements in them may have been caused by a combination of factors: intense topographic alterations and small scale of the architecture. In turn, on the eastern sector of the study area, along the valleys of the Cala and Rivera de Huelva rivers, present-day

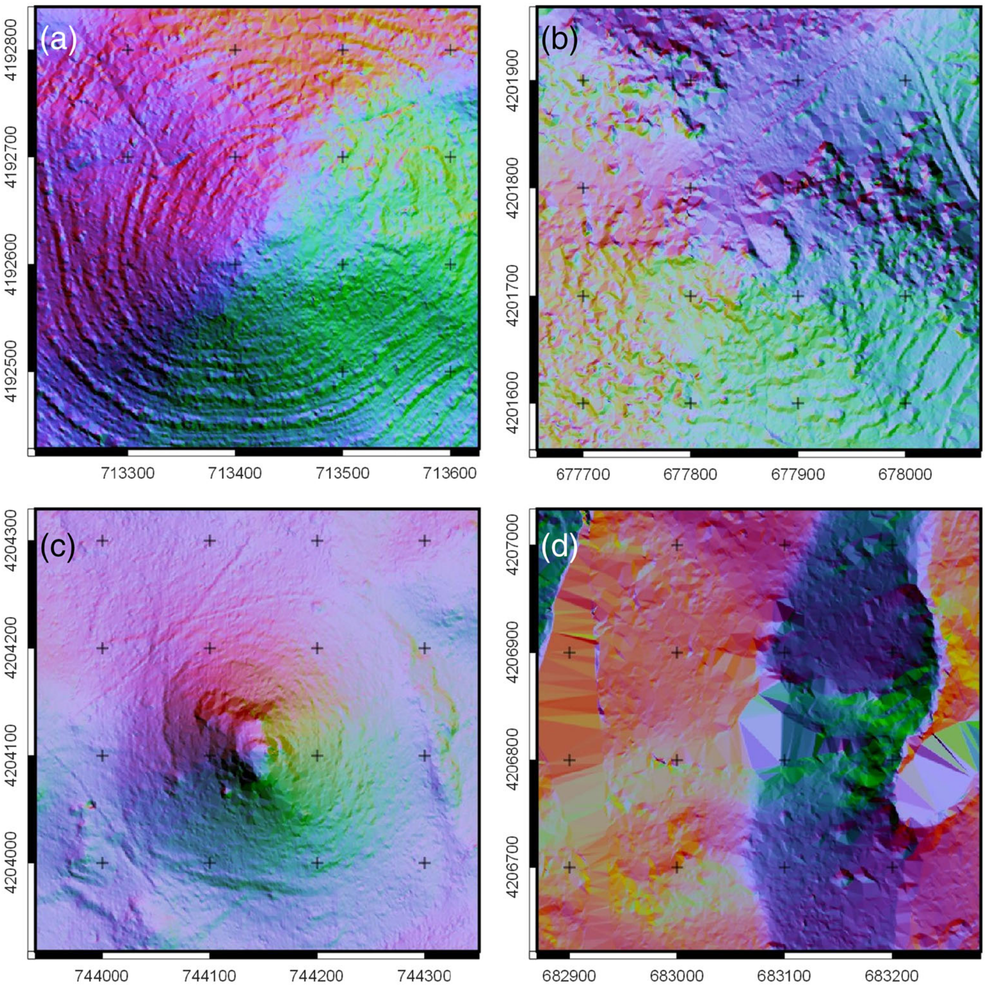

FIGURE 4 Unidentifiable settlements due to forestry works (a: El Tambor), telecommunication infrastructures (b: Alto del Naranjo), low resolution (c: El Almendro) and loss in classification (d: Castillo de Maribarba). Data: © LiDAR-PNOA 2014 CC-BY 4.0 scne.es. Coordinates: EPSG 25829 [Colour figure can be viewed at wileyonlinelibrary.com]

vegetational coverage is eminently of the 'dehesa'[2] type, and accordingly, the relief has not undergone severe transformations. In this sector, several BA settlements are known, which have very substantial walled features that are clearly identifiable in the laser altimetry. Another type of land use that caused substantial relief changes are infrastructures such a power lines or telecommunications. While both the towers and antennas needed for these infrastructures involve heavy transformations in the local topography, the latter are placed on locations with ample viewsheds, which often replicates the location of late prehistoric settlements (Costa-García & Fonte, 2017). This is the case with settlements such as Alto del Naranjo (CA) and La Traviesa II (CA/BA).

Regarding the second problem, it is worth noting that only when the available point density is higher than 0.5 p/m^2 has it been possible to detect human-made features on the LiDAR altimetry. In the cases analysed, those in which the density of points classified as ground is between 0.12 and 0.5 p/m^2, when interpolating a DTM with 1 m resolution the result is blurred and if is rasterized to 3 m resolution the structures are not detectable. At sites like Cansalobos and El Almendro, the raw data were quite insufficient, with the total density of returns standing below 0.5 p/m^2 and an average distance in excess of 1.5 m. To this, an element of loss implicit in the filtering process must be added, which for cases like Castillo de Maribarba and Cerro del Chinchato caused the density of Class 2 points to fall below 0.15 p/m^2, with points classified as vegetation exceeding those classified as soil by a factor of 2.5 in the former and 1.7 in the latter. This high proportion of nonusable returns is highly determined by the type and density of vegetational coverage, as Mediterranean sclerophyllous shrub areas are more impenetrable for laser pulses than those of 'dehesa' oak forests (Doneus et al., 2020). As mentioned above, an additional limitation of the PNOA's LiDAR data is that up to 47% of points are unclassified.

4.2 | Intrasite microtopographic and architectural analysis

For 20 of the sites included in our sample, the density of ground returns provided sufficient resolution for a precise intrasite architectural and microtopographic analysis (by the latter we mean analysis of

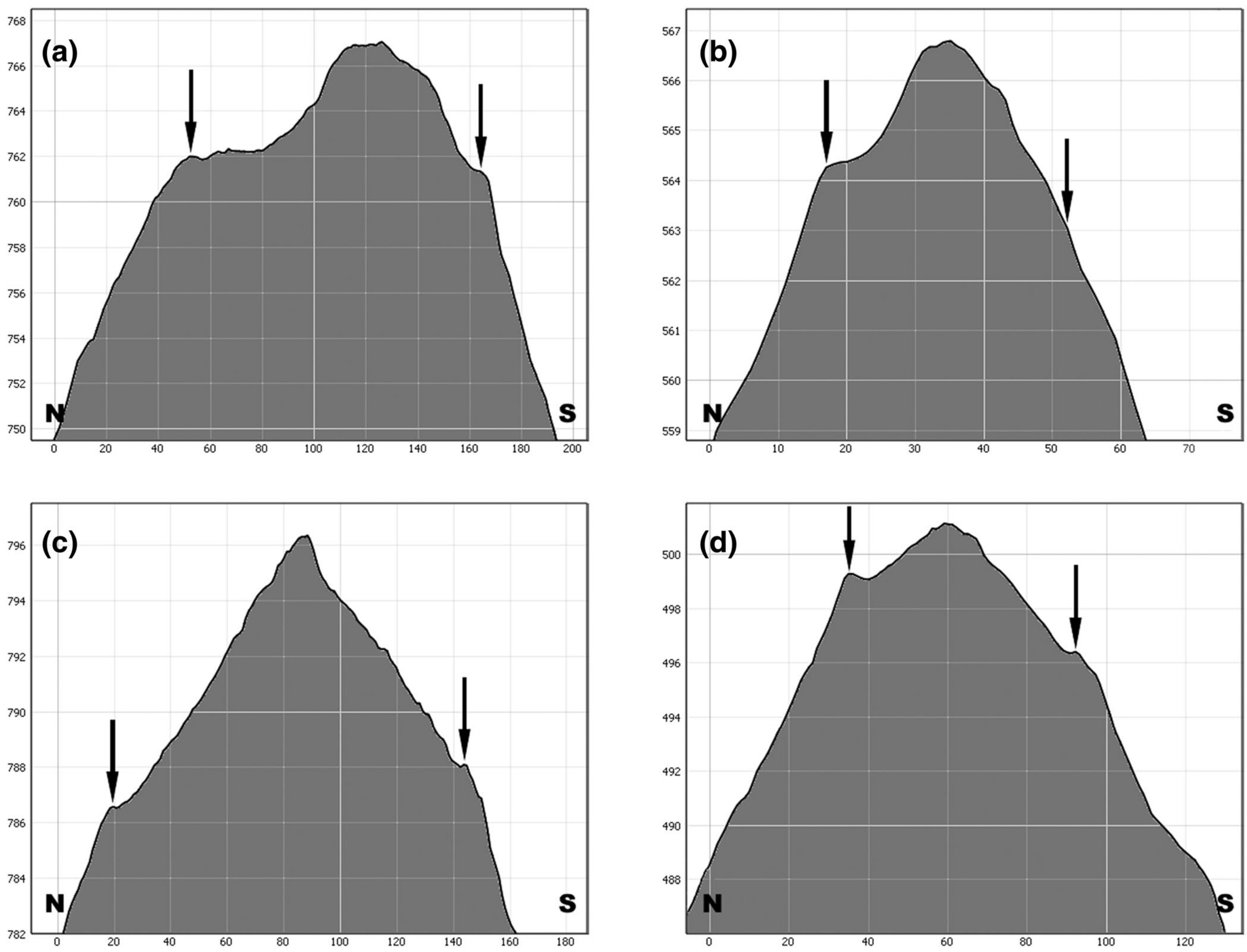

FIGURE 5 Topographic profiles for (a) La Bujarda, (b) Castillejos, (c) Cerro del Cojo and (d) Santa Marta II, showing the location of walled features. Factor Z $\times$10

variations in elevation ranging from 1 to 5 m). In these cases, transforming the values of the LiDAR-based DTMs in slope values led to a clear identification of the most conspicuous element in artificial reliefs: horizontal surfaces caused by terracing of the slopes and 'flattening' of hilltops. In some settlements, a single 'platform' level is observable, forming a flat plateau surrounded by steep sides, natural or artificial, as is the case with La Umbría, El Castañuelo, La Muela, Santa Marta III, El Torrejón and Cerro del Almendro (Romero Bomba & Rivera Jiménez, 2008). Other larger settlements do not only occupy the hilltop but sprawl over the hill sides, which were adapted for inhabiting by means of terraces, as is the case with Cerro del Cojo, Santa Catalina, Sierra de La Lapa and El Trastejón. In some cases, the upper terrace forms a small-sized 'plateau' in way of 'acropolis', which appears to be differentiated from the rest of the village by its perimetral wall, as see at La Bujarda, Los Castillejos, Las Pedreras, El Torrejón and El Trastejón (Hurtado Pérez, García Sanjuán, Mondéjar Fernández de Quincoces, & Romero Bomba, 2011). The contrast between the high-value pixels representing steep slopes and the neighbouring low-value ones representing 'plateaus' makes it possible to create a fairly accurate representation of the artificial topography at these sites. There are some clear examples of this. At El Torrejón, there are inner slopes of 15° surrounded by sides with up to 40°; at Cerro del Almendro, a central 'plateau' with less than 18° of sloping is surrounded by sides with up to 50° inclination; at El Castañuelo the same case is recorded, with inner slopes below 16° surrounded by slopes of between 20° and 35° on its edges (Figure 5).

The 'ring' of steep slopes that surrounds most of the settlements is sometimes natural, corresponding to rocky outcrops, ravines or simply very steep hillsides. This occurs both in small and large settlements. In larger settlements, artificial structures do also appear, with a linear shape and a sinuous layout, particularly in areas with less steep natural slope. In the DTMs, these lines are identifiable by their slopes greater than 30°, by their current width (between 7 and 10 m), by a difference in elevation between the base and its top (between 3 and 7 m) and by maintaining a constant height in their upper part. In the few excavated examples (only in El Trastejón and La Papúa II), large walled structures have appeared, built by accumulations of flattened slabs of shale rocks, with heights reaching up to 3 m, average widths between 1 and 2 m and sloping sides (Hurtado Pérez, García Sanjuán, Mondéjar Fernández de Quincoces, & Romero Bomba, 2011), similar to those of other walled habitats in southern Portugal (Gonçalves et al., 2013). In some settlements, these walls achieve a double function, both as defensive devices and supporting large terraces, dwellings and other facilities. These walls often surround the entire perimeter of the settlement, with lengths that reach up 676 m at Las Pedreras, 703 m at La Bujarda and 883 m at El Trastejón. An exceptional case is that of La Papúa II, with a wall totalling 3252 m in perimeter, which sets the boundaries for three different massive enclosures.

The layout of these walls normally follows the contour lines of the hillsides, but drawing sinuous forms with semicircular projections that advance along the line of the wall, creating protruding bastions. In addition to a structural function to reinforce the stability of the walls, these bastions probably also had a defensive purpose, as suggested by their location at corners, flanking the gates and supporting the most vulnerable sections of the walls. From the walled features excavated in La Papúa II (Hurtado Pérez, García Sanjuán, Mondéjar Fernández de Quincoces, & Romero Bomba, 2011) and in other contemporary BA settlements of the Iberian Southeast such as Peñalosa in Jaén, Castellón Alto in Granada or La Bastida in Murcia (Molina González & Cámara Serrano, 2004), it appears that these bastions were made by superimposing rows of medium-sized slate slabs joined with mud. In western Sierra Morena, they have a truncated cone-shaped with their diameter decreasing in altitude and have a radius at the base between 2 and 4 m. The distance between these bastions is highly variable, with a minimum of 17 m at Las Pedreras,

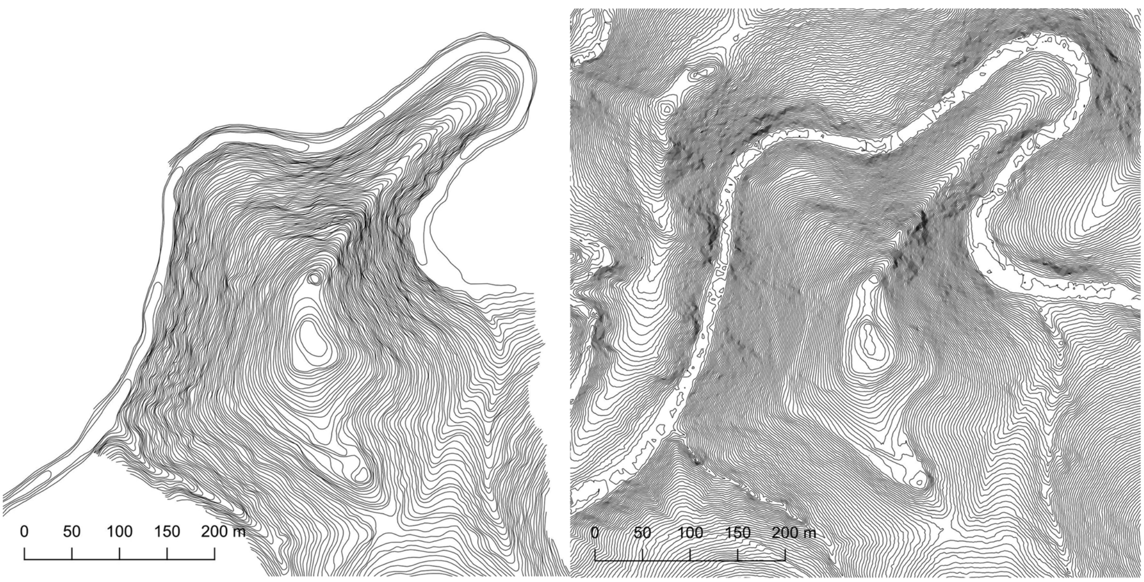

FIGURE 6 Topographic maps of El Trastejón hill produced by photogrammetric restitution (left) and by contouring from LiDAR (right). Left: Hurtado Pérez, García Sanjuán, & Hunt Ortiz, 2011

25 m at La Bujarda or 28 m at Cerro del Cojo. A special type of bastions is the pointed spurs that project the walls at some end of the enclosure, as observed in La Bujarda, La Lapa, Cerro Librero, La Papúa II, El Torrejón and El Trastejón. In the latter, this feature shows a difference of 13 m elevation at its southeastern end (Figure 6).

Especially interesting are the bastions that flank the access gates to the settlements, since they follow some rules common in the military architecture of the BA across the Mediterranean (Montanero Vico & Asensio i Vilaró, 2009). One of these rules consists of misaligning the wall line to design a jogged entrance, creating a corridor that allows an easier defence of its sides. These side-access doors are usually referred to as 'overlay doors'. In addition, wooden bridges could be installed on the forts to reinforce the door for a defence in height, and the gates that closed the enclosure would be supported on them. There is also a special reinforcement of these defences on the right side, in the direction of entry, probably in connection with the fact that attackers would have been more vulnerable on that side, as they held their shields with their left hands. In some larger settlements, two gates can be identified, a main one located at the most suitable access based on the low sloping and a smaller gate at the closest point to a watercourse, as observed in Castrejón de Capote, La Bujarda, Santa Marta II, La Papúa II, El Torrejón and Las Pedreras. The only one of these gates with forts that has been excavated, the one in the north-eastern section of La Papúa II, was 3 m wide, although cases such as San Blas in Cheles, Badajoz, have been documented with only 0.8 m wide in its southwestern gate near the river (Hurtado Pérez, 2004). The access roads near each settlement would start from these gates, but their layout has not left a mark on the current topography.

Altogether, LiDAR was able to detect a wide range of positive features, including perimeter walls, terraces, bastions, gates, acropolises and even roads. Conversely, no negative features such as ditches or pits were detected, despite the fact that they are abundant in CA settlements (less so in BA settlements). Obviously, the fact that they are currently filled with soil causes them not to present a significant variation in the topography of the terrain. Negative features are easier to detect through air photography, as they are often revealed by a denser vegetation. Negative features relatively common in 'Argaric' BA settlements, such as water cisterns, were not documented in the sample of sites studied here, but this may be explained by the different environmental and hydrological conditions existing in southeastern and southwestern Spain, whereby the former is much drier and more arid than the latter, thus demanding more complex hydraulic infrastructures. In general, with a 1 m DTM resolution, further interpolated from points with less than 0.77 p/m^2, positive features such as house walls were not detectable because of their narrower width. The most easily detectable features were, by far, terraces, both because of their size, usually in the dozens of metres in length and width, and because of their steep sides, with slopes ranging between 18% and 40%. Algorithms for convexity measurement detected terraces quite well.

LiDAR data were successfully used to produce contour maps of individual sites with very cost-effective results. A good example of this is El Trastejón, which in 1988 was mapped through a conventional—and costly—topographic survey that took several hours of fieldwork, whereas the 1 m desk-based LiDAR-derived contour map was produced in barely a couple of hours. Both maps are shown in Figure 6. A recent comparison of the quality of DTMs derived from LiDAR data of the Spanish IGN and from drone-supported photogrammetric restitution suggests that while UAV photogrammetry has led to a gain in time of fieldwork and the recording with the same equipment of features of difficult access due to steep terrain and/or great height that would normally require ladders or scaffolding, LiDAR is an extremely useful and precise tool to survey both individual sites and larger areas (Rouco Collazo et al., 2020).

4.3 | Site size

The study presented here confirms that, as well as drawing precise plans of major architectural elements, LiDAR data can be successfully used to establish the size of CA and BA settlements. In half of the settlements analysed here, LiDAR altimetry has led to a precise drawing of the settlement limits as bound by the walled features, although in some cases certain features, such as light dwellings or furnaces, may have existed outside those limits (Figure 7). While in surface surveys discrete sections of the walls, sometimes up to several hundreds of metres, could be recorded, remote surveys were able to fully draw the layout of the enclosures. This is of great importance, as often these hilltop sites are hard to get to and appear densely covered by a thick vegetation, which makes direct surveying strenuous and slow, if at all possible. The newly drawn LiDAR-based plans make possible establishing settlement size with metric precision (Table 4). Site size is an important parameter, as it has been variously used to estimate population size as well as settlement functionality and hierarchy within the context of regional settlement patterns (Chapman, 1990; García Sanjuán et al., 2011; Legarra Herrero, 2014). Although the average area of these sites is 1.2 ha and the median 0.7 ha, their sizes are very unequal. Excluding La Papúa II, which is an exceptional case, the largest of them is Sierra de La Lapa with 42 836 m^2, which is 37 times larger than the smallest: Cerro del Almendro with 1158 m^2. The lower tier, including settlements with less than 1 ha, amounts to half the sites included in this study. These settlements are usually located on small hills very close to the main water courses on the banks of Chanza, Huelva and Cala rivers and within short distance of each other, less than 10 km in a straight line. The medium tier includes six fully walled settlements with sizes between 1 and 3 ha, located in three of the cases (Cerro del Cojo, La Bujarda and Castrejón de Capote) in the headwaters of their hydrographic basins and in the remaining three (Castillo, Las Pedreras and Santa Catalina) in their middle courses, between 15 and 20 km apart. The upper tier includes basically two settlements: Sierra de la Lapa in the Múrtigas river basin, with 4.28 ha, and El Trastejón on the Ribera de Huelva riverbank, with 3.24 ha in its lower enclosure (excluding La Atalaya de El Trastejón, which appears to be an annex facility). These two settlements are located in the centre of their respective valleys, and both display large

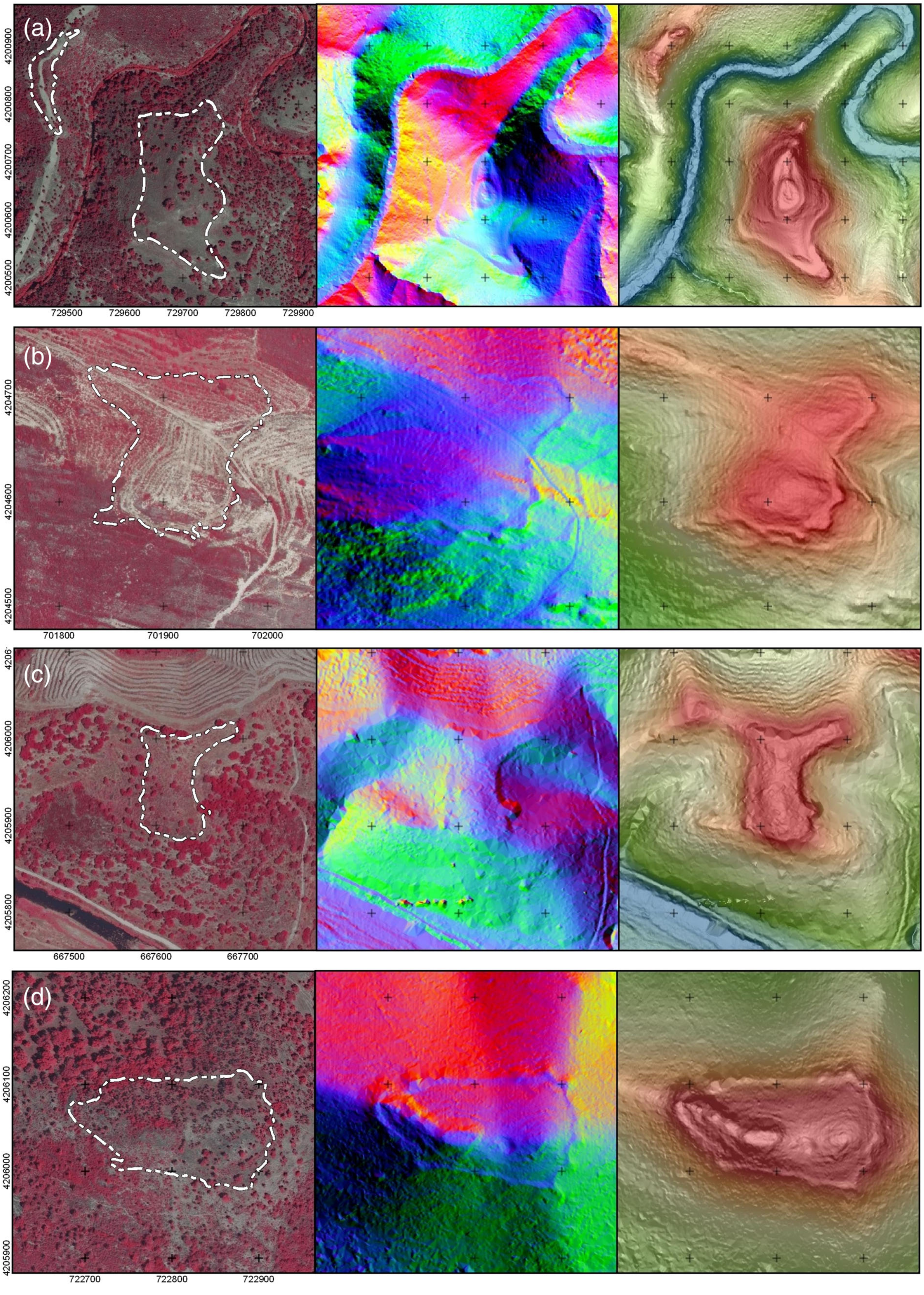

FIGURE 7 Infrared orthophotography, PCA of hillshade and hypsographic map of (a) El Trastejón, (b) La Bujarda, (c) El Torrejón and (d) Las Pedreras. Orthophotography: © Red de Información Ambiental de Andalucía 2017. Data: © LiDAR-PNOA 2014 CC-BY 4.0 scne.es. Coordinates: EPSG 25829 [Colour figure can be viewed at wileyonlinelibrary.com]

terraces supported by massive walls. In the watersheds of Cala and Chanza, no settlements of this category appear, although due to their central position this function could have been fulfilled by La Traviesa and Bejarano, today largely destroyed by forestry works. La Papúa II, with a total size of 16.63 ha, is an outlier, possibly the most high-ranking BA settlement in the whole of the region (Hurtado Pérez, García Sanjuán, Mondéjar Fernández de Quincoces, & Romero Bomba, 2011).

4.4 | Settlement patterns

The LiDAR survey undertaken for western Sierra Morena fully confirms that CA and BA settlement patterns are very similar to the ones described in other southern Iberian regions, as briefly outlined above. This is particularly the case for southern Portugal and the Spanish Southeast. For southeastern Spain, where many more sites have been excavated than in the southwest, Chapman (1990) suggested CA settlement sizes ranging between 0.3 and 5 ha (the biggest one is Los Millares), with two thirds of them being smaller than 1 ha. This is pretty much in line with the results obtained for western Sierra Morena after the LiDAR survey presented here. As far as the BA is concerned, Chapman calculated for Argaric settlements sizes somewhat greater, between 0.8 and 6.5 ha (Cuesta del Negro is the largest), with only a quarter under 1 ha. Again, this is compatible with the results achieved by the LiDAR survey presented here for western Sierra Morena, with several settlements between 1 and 3 ha (La Bujarda, El Trastejón and Las Pedreras) and some even bigger ones, with La Papúa II standing out at approximately 12 ha.

For the Spanish Southeast, Legarra Herrero (2014) established a three-tier hierarchy, including 'central settlements' with more than 2 ha, 'secondary' settlements between 0.3 and 2 ha and smaller ones between 0.1 and 0.3 ha. In this study, the 'central' settlements were characterized by areas ranging from 2.19 ha at El Argar to 4 ha at La Bastida, but bigger sizes do also appear in other noncentral sites such as Cabecicos Negros (11 ha), Cerrillos (6 ha) and Cerro del Pajarraco (7.7 ha). Valencian BA settlements have also been categorized in a three-tier system (Jover Maestre et al., 1995). In the Vinalopó valley (Alicante), upper-tier settlements have maximum sizes between 0.1 and 0.3 ha. Since the middle of the second millennium BCE, new and larger settlements appeared, such as Les Raboses with 2500 m^2 with four levels of terraces and a wall at the bottom, Oropesa la Vella with a walled enclosure reinforced by bastions, Sopeña de Segorbe with 6000 m^2 and Cabezo Redondo in Villena, with an area of 8000 m^2 (Pedro Michó & Martí Oliver, 2004). Excavation data are still too scarce for BA settlements in the Western Sierra Morena range, but with the known evidence in hand (mostly from El Trastejón and La Papúa II plus some burial locations), there is every reason to expect a similar arrangement of sites, as suggested many years ago (García Sanjuán, 1999).

Thus, beyond the identification, measurement and description of features at specific settlements, LiDAR has great potential to reveal patterns in the structure (or hierarchy) of a region's occupancy at any given time. Observed similarities between the CA and BA settlement patterns of western Sierra Morena and other Iberian regions (notably, the southeast, for which better-quality data are available) include settlement size, locational preferences (including the pervasiveness of hilltop locations) and the presence of substantial stone-made civil and defensive infrastructures. These characteristics, identified for the 'Argaric' area since the late 19th century by the Siret brothers (Siret & Siret, 1890), are in fact common throughout southern Iberia, from the Portuguese Algarve to the Valencian region (García Huerta & Morales Hervás, 2004).

5 | CONCLUSIONS

The data pertaining the settlement dynamics of Sierra Morena in the CA and BA presented here, compiled on the basis of a LiDAR-based analysis, complements and expands the previous knowledge gathered after years of fieldwork (with the support of aerial photography). Several conclusions can be drawn from this study:

1. Public, freely accessible LiDAR data issued by the Spanish government revealed high-quality data for 20 out of the 36 selected settlements.
2. Detected microtopographic features include walls, bastions, terraces, acropolises, possible embankments, gates and roads.
3. The spatial and cartographic details of such detected features match or surpass those obtained through direct fieldwalking and/or air photography.
4. For the remaining 16 settlements, LiDAR data failed to provide accurate microtopographies of features previously identified through fieldwork on account of changes in the topography or insufficient data resolution.
5. Provided that topographic conditions are not too altered by land use (especially, by re-afforestation), LiDAR public data show substantial potential to identify, represent, map and interpret prehistoric settlements in mountain environments, including precise renderings of specific architectural features.
6. LiDAR data can be used as an affordable, reliable and accurate data source to map late prehistoric archaeological sites in regions for which no previous field work and/or inventorying work is available.
7. LiDAR data can also provide an empirical basis to interpret settlement patterns in terms of population density, hierarchical ranking and locational strategies.

Notwithstanding the fact that, in areas where no previous fieldwork has been undertaken, the ability of LiDAR data to automatically map and analyse depends on ground truthing (as a form of empirical corroboration and 'quality control'), particularly in procedures supported by AI, the results obtained in this study show that LiDAR has great potential for the study of CA and BA societies across southern Europe and the Mediterranean. This is particularly necessary in order to establish the chronology of sites for which architectural features are few, small and/or nondescript. A good example of this, which is currently under study, is mining features commonly associated to CA and BA settlements in western Sierra Morena, such as trenches, shafts and dump sites. On a LiDAR cartography, the image of such features can be very similar for sites dating to a wide chronology, from the CA to the Middle Ages.

It is also worth mentioning that LiDAR-derived microreliefs can be envisaged as a basic constituent of prehistoric landscapes, incorporating a history of construction, use and reuse like a palimpsest (Johnson & Ouimet, 2018), as well as a series of long-term geomorphological transformations and post-depositional alterations. The interpretation of microreliefs as a succession of changes over time is useful to identify modern land uses as a determining element in order to assess the usefulness of ALS techniques. Comparing the 20 settlements of the study area for which features previously identified through fieldwork have been successfully mapped through LiDAR with the 16 for which this has not been possible, it becomes clear that certain contemporary land uses prevent the successful use of LiDAR for CA and BA settlements. This includes industrial forestry, irrigation agriculture, large-scale mining and major infrastructures. It goes without saying that the same is true for those CA and BA settlements on which major occupancy, including castles, occurred in the Middle Age (as is the case of Cala, Aracena, Cortegana and Cumbres Mayores). In a way, all the settlements successfully mapped in this study have in common that they *failed* to sustain a long-term occupation: they were abandoned at the end of the BA or during the IA and were never reoccupied in the Middle Ages.

The results obtained in this study also suggest some of the caveats and problems to be considered when using LiDAR in other Mediterranean regions. One interesting point concerns vegetation coverage. Unlike deciduous forests of the northern reaches, where a leaf-free season allows an optimal laser penetration, Mediterranean xerophilous tree and bush vegetation coverage is constant throughout the year. Dehesa-like Mediterranean oak-tree forests (with *quercus suber* and *quercus ilex*) allow for good resolutions once returns are classified, as there is sufficient distance between trees and the canopies are not so dense as to prevent ground-type returns. In turn, while pine forests offer less resolution, areas covered with dense Mediterranean bush vegetation such as rockrose (*cistus ladanifer*), gorse (genista scorpius), mastic (*pistacia lentiscus*) and arbutus (*arbutus unedo*) are impenetrable with the available density of pulses. At any rate, these limitations do also affect field walking. While dehesas are normally relatively amenable to direct survey, dense bush areas are often impenetrable.

In summary, the application of LiDAR-based surveys would greatly help to enhance and homogenize the data pertaining CA and BA settlements and other periods. In the sample of 36 settlements studied in this paper, for which previous documentation existed in the form of plans, photographs and written descriptions, although limitations in raw data accuracy and changes in land use made it impossible to obtain high-quality plans for about half of those sites, ALS reached satisfactory results for the other half, improving previously existing records. LiDAR data allow for the identifications and characterizations of specific features and architectural elements of matching or superior quality to that already achieved by other means, such as fieldwalking and/or air photography. Paraphrasing Lozić and Štular (2021), the case study presented here confirms that LiDAR data can fundamentally redefine archaeological survey work and spatial analysis by splitting the activities into desk-based interpretative mapping and field-based ground assessment, by enabling unsurpassed metrical accuracy, by providing the widest possible landscape context and by enabling a precisely targeted and planned fieldwork that can be carried out very efficiently. LiDAR can provide massive advantages to the cartographic representation of CA and BA settlements: While in surface surveys only isolated sections of the walls, mostly a few dozen metres in length (at best, after strenuous vegetation clearance, several hundreds of metres), could be recorded, LiDAR has been able to fully draw the layout of whole enclosures measuring several hundred metres in perimeter. This is of great importance, as, often, these hilltop sites are hard to get to and appear densely covered by a thick vegetation, which makes direct surveying highly energy and time-consuming and slow, if at all possible. Thus, the new LiDAR-based plans make possible the delimitation, planimetry and mapping of the settlement size with metric precision.

Furthermore, LiDAR data can help to substantially improve conventional interpretations in terms of settlement patterns (population density, hierarchical ranking and locational preferences). The pattern resulting from the case study presented here show that both in the CA and BA, settlements were located on hill tops, although some substantial differences emerge in terms of locational strategies. In the BA, settlements were built on very steep, easily-defensible hilltops and were provided with larger and more substantial stone-walled infrastructures, some of them of clearly defensive nature, a trend observed across the whole of southern Iberia. This defensive concern was much more marked in the BA than in the CA—see full discussion in García Sanjuán et al., 2011. Indeed, the application of LiDAR-based surveys would greatly help to enhance and homogenize the data pertaining to CA and BA settlements, and other periods in which similar features were built, such as the Iron Age or the Middle Ages. In turn, in Iberia, this would contribute to challenge long-held notions regarding the 'uniqueness' of the Argaric BA culture, thus providing a more encompassing and reliable perspective of prehistoric settlement patterns.

Despite some of the problems mentioned above regarding data accuracy, the application of LiDAR altimetry is nonexpensive and relatively uncomplicated, given the availability of freely-accessible public data, which are improved every 6 years in Spain. In any case, public data need to be increased in resolution and classification accuracy for more effective archaeological use. In their present configuration (more so in the future, as precision increases), LiDAR data can significantly contribute to refine, enhance and homogenize the description of CA and BA settlements, both in terms of locational preferences and architectural configuration. Many of the features normally present at these sites can be accurately mapped by LiDAR altimetry, as shown by about half the cases examined in this paper. The evidence thus represented accurately reflects features such as terraces, defensive walls with bastions and gates, common in later prehistoric sites and particularly in BA. LiDAR-based technology will no doubt help predict the location of such kinds of settlements wherever, unlike the Sierra Morena region studied here, no earlier work has been carried out and no previous documentation exists. ALS projects have great potential to support and expand regional and national inventories of prehistoric sites, thus contributing to a better protection of the archaeological heritage.

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CONFLICT OF INTEREST

There are no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the Spanish National Geographic Institute (http://www.ign.es/web/ign/portal). These data were derived from the following resources available in the public domain: Spanish National Geographic Institute (http://centrodedescargas.cnig.es/CentroDescargas/catalogo.do?Serie=LIDAR).

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ENDNOTES

[1] http://centrodedescargas.cnig.es/CentroDescargas/catalogo.do?Serie=LIDAR

[2] The dehesa is a multifunctional agro-sylvo-pastoral system and cultural landscape found in central and south-western Iberia, based on human-managed natural forests of oaks, usually holm oak (Quercus ilex) and cork oak (Quercus suber). As well as forestry exploitation, the dehesa is used primarily for grazing of animals, very especially Iberian pigs, which are allowed to roam freely, feeding on acorn.

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