# Evolutionary model and palaeoenvironmental interpretation of the La Codera archaeological complex (Ebro Basin, NE Spain)

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## Abstract

La Codera archaeological site is one of the most important settlements from the 1st Iron Age in the Ebro valley, dated between *ca.* 800 795 and *ca.* 460 cal. BC. The archaeological area also includes other later settlements. We analyzed the geomorphological context of the area by conducting a geoarchaeological survey and sampling. We also completed the evolutionary framework of the settlement, including paleoenvironmental information. Four slope stages (S1–S4) were identified, some of them related to fluvial terraces. Stages S4 and S3 are two old residual slopes dated to the Pleistocene, without evidence of human occupation. Older features related to human occupations are charcoals dated to Chalcolithic times from T2 terraces of La Codera stream. Slope S2 contains archaeological remains from the 1st Iron and Bronze Ages. Therefore, La Codera and its slopes were occupied during the Bronze Age, before Iron Age settlements. Slope S2 formation corresponds to the stable environmental stage known as the Iron Age Cold Epoch, or 2.8 Bond Event, also identified in many areas of the Ebro Depression. This period was followed by an erosive stage after the Roman Epoch (possibly during the 1.4 Bond Event). Later, a new slope (S1) formed, together with a new terrace (T1). This slope includes walls and ceramics from Iberian, Roman, and Medieval times toward the northeast of the settlement. These features make it possible to infer that this last accumulation formed during the cold stages of the LIA.

**Keywords**: Geoarchaeology, Upper Holocene, 1st Iron Age, Bronze Age, Bond Events, *talus flatirons*.

## 1. Introduction

In drylands, the dynamics and erosive capacity of some geomorphological processes can significantly alter archaeological sites. In these cases, only the exhaustive prospection of morphosedimentary records of the surroundings allows one to reconstruct the original characteristics and chronology of the archaeological site and determine the degradation causes and processes (Peña Monné, 2018).

The Ebro Depression is the largest dryland region in the Western Mediterranean (Figs. 1a, 1b). Although at present many areas are unfavorable to human occupation, in the past this region was densely occupied, as shown by the presence of archaeological remains. Many geoarchaeological studies have been conducted in the central Ebro valley. These studies have made it possible to establish evolutionary models from residual archaeological records combined with paleoenvironmental reconstructions of different cultural epochs. Among these, Peña Monné and Rodanés (1992), Peña Monné and González (1992), Peña Monné et al. (1996, 2022), Pérez-Lambán et al. (2014), and Picazo et al. (2022) focused on the evolution of Holocene slopes. Outstanding geoarchaeological and paleoenvironmental records have also been obtained from the system of Holocene terraces on the floors of semiarid valleys in the Ebro depression (Peña-Monné et al., 2022). This is the case with the Huerva River valley (Peña-Monné et al., 2000, 2004; Pérez-Lambán et al., 2018), the northern side of the Sierra de Alcubierre (Peña-Monné et al., 2018), and the surroundings of Zaragoza city (Van Zuidam, 1975; Burillo et al., 1985; Peña Monné, 1996; Constante et al., 2010, 2011, Peña-Monné et al., 2021). In other areas of the Mediterranean Sea, especially Greece and western Turkey, Holocene reconstructions have been based on littoral plains (Brückner, 1986; Van Andel et al., 1990), while slope records are scarce. Similar archaeological studies have been conducted in the southwest of the United States (Huckleberry et al., 2013; Onken et al., 2014) and South America, both in coastal areas (Manners et al., 2007; Gayo et al., 2012; Keefer et al., 2003) and inner valleys (Sampietro-Vattuone and Peña-Monné, 2016; Peña-Monné and Sampietro-Vattuone, 2014, 2019). In general, it is a complex task to establish whether environmental records were produced by climatic or anthropogenic causes. In fact, some studies have shown that both causes may have similar morphological consequences (Bintliff, 1992; Butzer, 2005; Fuchs, 2007; Zielhofer et al., 2008; Constante et al., 2011; Bellin et al., 2013; Ackermann et al., 2014; Sampietro-Vattuone et al., 2018, 2019).

The archaeological complex of La Codera is located next to the confluence of the Cinca and Alcanadre Rivers, in the central-eastern sector of the Ebro depression (Fig. 1c). The archaeological excavations conducted since 1982 at La Codera archaeological site (Montón, 2003-2004, 2020) provide an overview and chronology of the human occupation of this territory from the 1st Iron Age to the Ibero-Roman Epoch. The aims of this study were (1) to undertake a detailed survey of La Codera archaeological site, including the analysis of Holocene slopes and fluvial terraces around the site; (2) to construct an evolutionary geoarchaeological model to fill an information gap in the literature on human occupation of La Codera; (3) to relate the obtained reconstruction with other models of the northeastern Iberian Peninsula; and (4) to interpret the influence of human activity and Holocene environmental changes at regional and global scales within the framework of the identified evolutionary processes.

### 1.1. Geological and geographical framework of La Codera

From a geological point of view, the area is part of the Ebro tectonic depression filled by continental deposits during the Cenozoic (Fig. 1d). It is composed of horizontal Miocene continental sediments of the Agenian age (Early Miocene). These accumulations belong to the Alcubierre Fm. (Quirantes, 1978), more specifically the Torrente de Cinca-Alcolea and Galocha-Ontiñena units (Salazar et al., 1990). Four sedimentary units were identified at La Codera, as shown in Fig 2, the geomorphological map (Fig. 3), and transverse profiles (Figs. 4a, 4b, and 4c):

The Cinca River, located approximately 400 m to the west of La Codera, is the general base level of the region (Figs. 1c, 4b, 5). It is one of the largest tributaries of the Ebro River and flows down the southern Pyrenean slope. Its headwaters collect the water of the highest sectors of the ranges with abundant snowmelt contribution; therefore, this river has a pluvio-nival regime. Its annual average flow at the Fraga gauging station is 81.4 $m^3/s$, and its specific flow is 8.33 $l/km^2/s$, with an annual average flow of 2566 $hm^3$. Higher flows occur in autumn due to DANA cut-off low (2587 $m^3/s$ in Fraga on October 22nd, 1977) (Sánchez Fabre et al., 2004). At present, this river is regulated by dams and irrigation channels along the basin; however, until the 1970s, the channel was typically braided.

The present climate is continental Mediterranean with average rainfall between 417 mm (Sariñena) and 346 mm (Villanueva de Sijena), because it is an arid region. The average annual temperature is approximately 15 ºC. The vegetation is adapted to soils and microclimates of different environments. Limestone platforms have gall oaks (*Quercus faginea*), Iberian oaks (*Quercus ilex*), junipers (*Juniperus thurifera*), and Aleppo pine (*Pinus halepensis*), accompanied by Mediterranean scrub. Lower areas, with marls and clays, are salty and the dominant species is albardine (*Lygeum spartium*), while tamarix (*Tamarix africana* and *Tamarix gallica)* are present in wetter streams.

## 1.2. Archaeology of La Codera

Many archaeological sites are located in the triangle formed by the Alcanadre and Cinca rivers before they merge, which shows intense occupation between the middle of the Bronze Age (*ca.* 1600-1300 cal. BC) and the Iberian-Roman Epoch (5th century cal. BC to 5th century cal. AD). The most important site is the settlement of the 1st Iron Age (*ca.* 800 to *ca.* 460 cal. BC) named La Codera. The first archaeological excavations were made in 1982 in the funerary area composed of two tumular necropolises (Montón, 1992, 2002). Research was interrupted until 1997 when systematic excavations resumed and have continued until the present (Montón, 2015, 2018; Seguí, 2017). The settlement of the 1st Iron Age archaeological site is located on an elongated, narrow, slightly curved rocky spur (Figs. 3, 6a, 6b, 6c). It has a surface of about 3500 $m^2$, with 105 m in length and 30 m in width. It is about 228 m a.s.l. and 60 m above the present Cinca River height. To protect the access to the spur, a 40-m-long wall was built, containing a square tower in the center and two semicircular towers at both ends (Fig. 6b). It is the most outstanding construction in the village, and it certainly required considerable collective effort (Seguí, 2017; Montón and Seguí, 2018). The entrance to the village was through a ramp between the central and western towers (Montón, 2018). This type of defensive construction is also present in other sites of the Ebro valley, such as Els Vilars (Arbeca, Lleida) (Junyent and López, 2016), where phases 0 and I are contemporaneous with La Codera settlement, and Cabezo de la Cruz (La Muela, Zaragoza) (Picazo and Rodanés, 2009; Rodanés and Picazo, 2013-2014), whose phase II combines a large defensive wall with attached towers and a moat.

Thirty-eight houses were identified on the perimeter of the settlement. A street runs parallel to the wall and another one cuts longitudinally across the village (Montón, 2003-2004). Most houses on the eastern side of the village have been lost to erosion. The western side is better preserved. Two cisterns are located at the southern end of the settlement (Figs. 6b, 6c). They were excavated in the Miocene substrate, and a wall built of small blocks surrounds the sides of each cistern. They belong to two different occupational periods and represent a valuable record of the hydraulic structures used at those times. There are two necropolises, one located 200 m to the northwest of the site and the other one 400 m to the west (Figs. 3, 6a). Ten tumuli were excavated in the former and 23 in the latter. The tumuli are either rectangular or circular structures, where cremation was practiced. Grave goods are scarce but similar to the artifacts found in the village (Montón, 2002).

Twenty radiocarbon datings were obtained from the village of La Codera (11) and the West Necropolis (9). Village datings are between 2765 ± 40 BP (GrA-34176, 1007-803 cal. BC, Table 1) and 2480 ± 35 BP (GrN-26052, 773-423 cal. BC, Table 1). West Necropolis datings are between 2610 ± 40 (GrN-26966, 896-574 cal. BC, Table 1) and 2380 ± 35 (GrA-26135, 726-390 cal. BC, Table 1) Constructive characteristics, settlement patterns, and more than 70,000 recovered objects date the settlement to the 1st Iron Age (Montón, 2015). The origins of the village are linked to the Segre-Cinca Group of the Urnfields (Ruiz Zapatero, 1985; Montón, 1992) and Mediterranean influences (Rodanés and Picazo, 2018). However, there are features of the material culture, especially the ceramic forms resembling the types of Los Monegros (Montón, 2017, 2020). Only some surface surveys and specific excavations were conducted at the archaeological sites of the Iberian and Urnfield sites located in the surroundings of the settlement from the 1st Iron Age (Montón, 2020).

## 2. Methodology

Three detailed geomorphological maps were drawn at different scales, as proposed by Peña Monné (1997). Orthoimagery obtained through SfM photogrammetry was used as a cartographic basis. Vertical photographs were obtained with a sUAV at a height of 60 m for the general map (Figs. 3, 6a) and at a height of 30 m for the detailed map and DEM (Figs. 6b, 6c, 7). A DJI Phantom 4 sUAV was used with a FC220 (12.4 Mpx) camera. A flight was planned using Pix4DCapture in an Android environment. Photographs were processed using Agisoft Metashape Professional v.1.5.1. The obtained orthoimage has a resolution of 2.36 cm/pix and DEM 4.72 cm/pix. Field observations were recorded on these images using a Samsung Tab S2 tablet with QField app. Topographic cross-sections (Fig. 4) were drawn using the DEM and the geomorphological information gathered in the field.

Holocene aggradation stages are numbered from the youngest to the oldest stages—as is frequently done in other studies from the Ebro Basin (Peña-Monné et al., 2019)—because the number of older stages is unknown. In addition, references to the stages proposed by Peña-Monné et al. (2022) are included.

Based on the geomorphological maps and orthoimagery, a geoarchaeological prospection was conducted on slopes and terraces around the archaeological sites. Fifteen geoarchaeological records were obtained and included in the evolutionary model of La Codera. Some of them provided potsherds that were classified and used as relative chronological information, and three charcoal samples were radiometrically analyzed at the DirectAMS Laboratory (USA). Later, they were calibrated using Oxcal v. 4.3 over the IntCal 20 curve (Reimer et al., 2020), expressed as 1σ and 2σ.

Forty charcoal fragments from three samples (LC-7, LC-8, and LC-9) were analyzed. Sediment samples were processed by dry-sieving with a 2 mm mesh size to recover carbonized organic materials (LC-7, LC-9). Wood charcoal analyses followed the standard methods in anthracology (Vernet, 1973; Chabal et al., 1999). Microscopic wood anatomical features of each fragment were observed along the three anatomical planes under magnifications between ×50 and ×600 using an incident light dark/bright field Leica DM2700M microscope. Each fragment was manually broken, and the anatomical patterns of wood were observed along three anatomical sections: transverse (TS), radial longitudinal (RLS), and tangential longitudinal (TLS) sections. Analyses were carried out at the Laboratory of Prehistory of the University of Zaragoza (Spain). Botanical identifications were made by reference to wood anatomy atlases (Schweingruber, 1990) and modern carbonized wood reference specimens. Nomenclature follows the guidelines in Flora ibérica (Castroviejo, 1986–2012).

## 3. Results

The area has a structural relief, with step platforms or *muelas* and buttes with marly taluses (Figs. 3, 5). This arrangement is typical of the central-eastern part of the Ebro valley (Los Monegros and Bajo Cinca district). The upper platform (248–251 m a.s.l.) topographically dominates the landscape over the lower platform, where La Codera is located (228 m a.s.l.) (Figs. 3, 5). This platform is also higher than another one where the road is located (186–194 m a.s.l.). It extends up to a steep scarp over the Cinca River (162 m a.s.l.) located to the west of the archaeological site (Figs. 3, 4b, and 5).

A stream network tributary of the Cinca River drains the area. Notably, La Codera stream is located in the center of the geomorphological map (Fig. 3), to the south of the site (Figs. 4c, 5). This ephemeral stream drains the slopes of the lower limestone platform and flows into the Cinca River, developing a deep incision to adapt to the fluvial base level. The past intense lateral dynamics of the Cinca River promoted the progressive retreat of the headwaters of La Codera stream by headward erosion. Due to the evolution of this process, the lower platform has been cut into a scalloped shape by the activity of the marginal tributaries (Figs. 3, 4b, 4c, 5). There is an unevenness of approximately 30–40 m between scarps and the stream floor. The same process occurred on the northern stream, situated between La Codera and the northern butte, with Iberian settlements at its foot (Fig. 3).

### 3.1. Present slope dynamics

The Iron Age La Codera archaeological site is located on a slightly curved spur over the lower platform (Figs. 6b, 6c). It is bordered by steep limestone scarps 40 m higher than the surrounding valleys located to the south, southeast, northeast, and southwest. The spur is connected to the platform only in the northwest, where a large defensive wall protected the settlement. There are no defensive walls surrounding the site, although perhaps there was one reinforcing the defensive role of the natural scarp. According to the orthoimage of the site, it is evident that many house walls collapsed due to the scarp retreat, and part of the limestone blocks from the constructions are scattered on the slopes. The scarp retreat was especially intense at the southern end of the site (Figs. 6b, 6c, 7),

The great unevenness between the scarp and the valley floor is the first factor influencing the activity of erosion processes. It is a cliff-slope morphology (Fig. 7) composed of a 3–5 m vertical scarp followed by an upper rectilinear slope (40°–35º) on the southern and southwestern slopes; then a gentle slope (35°–25º), lightly concave at the base, continues downward, connecting with the horizontal surfaces of shoulders or the valley floor. The gradient is 5° to 10º smaller on the northeastern slopes, where slope deposits are more regularized.

This gradient is related to the contrasting Miocene lithologies of La Codera and its surroundings. The upper limestone scarp of unit 2 is the most resistant layer. Other minor scarps are visible in unit 1 due to the outcropping of sandstone layers (old paleochannels) between marly deposits (Figs. 4b, 4c, 7). Although paleochannels form centimetric scarps, differential erosion makes them protrude in the upper section of the southwestern slopes (Fig. 7). In many sectors, these scarps are thinner and recovered under a detritic accumulation, regularizing the slopes in different evolutionary stages. An important factor is the high calcium and sodium sulfate concentrations in the Miocene marls and clays of the region. The influence of these components on the erosive processes was highlighted by Peña-Monné et al. (2018, 2022) and Picazo et al. (2022) in Los Monegros and Hoya de Huesca (northern sector of the Ebro Depression). Rock moistening favors salt dissolution and precipitation, promoting the rupture of its internal structure by haloclasty and dry/wet cycles, notably increasing the dispersive properties of the soils (Jones, 1994). The most outstanding result of this process is the fast formation of sub-parallel rills, as well as piping (Harvey, 1982). Both morphologies are connected, forming complex networks of pipes, especially in the southern slopes (Fig. 7). The largest collapses occurred in the secondary scarps described in unit 1; the marly formations located under the scarps accumulate humidity, increasing water circulation through inner galleries that may collapse, and the upper block may sink. The resulting forms are concave niches, especially in the middle section of the slopes, accompanied by collapsed depressions and detached blocks (Fig. 7). Fast process evolution is important for understanding the landscape dynamics in the area.

Lastly, it is necessary to consider the semiarid climatic characteristics of this Mediterranean continental area. The tendency toward highly concentrated rains, especially convective storms during the summer, enhances the aforementioned factors (Bryan and Yair, 1982). The environmental conditions favoring erosion differ according to relief orientation. Erosion is higher in the south-facing areas, where vegetation is under great hydric stress, in contrast to north-facing slopes with less evapotranspiration (Fig. 7).

### 3.2. Slopes and inherited terraces

There are sectors with inherited morphologies next to the eroded areas. These morphologies are currently eroded by the incision of the streams that reach the marly substrate. The most prominent inherited forms are slopes developed under environmental conditions different from the present ones, probably a different climate. These landforms can be divided into groups according to their topographic position, conservation, and deposit content. This differentiation makes it possible to infer a chronological order and to propose stages separated by changes in environmental conditions.

### 3.2.1. Pleistocene slopes and terraces

Older stages are small remains of slopes separated from the scarps. There are only a few of them around La Codera. The stages furthest from the cornice, and therefore the oldest, are near the Cinca River (Fig. 4c, Fig. 8a). The oldest stage is named **S4** due to its position and connection with the T4 terrace of the main river. Morphologically, the next stage of the slope (**S3**) is represented by a small hill located at the foot of the southeastern end of the archaeological site. It has limestone fragments on its top, which come from the erosion of the upper scarp before its retreat (Figs. 3 and 8a). It did not provide elements to establish its age. There are other remains of this stage close to the southern side of a nearby hill disconnected from the rest (Fig. 8b). A fluvial terrace of the Cinca River connected with an equivalent S3 slope—close to Chalamera (Fig. 1c)—was radiocarbon dated to 16.4 ± 120 BP (20128-19518 cal. BP 2σ) (sample CHA-1 in Table 1). The few remains of these old stages (S4 and S3) have a triangular shape with a narrow apex facing the upper scarp and a larger reverse side with a straight-concave profile. This type of morphology is known as talus flatiron and it is very common in the Ebro Depression (Gutiérrez et al., 1996, 1998; Peña-Monné et al., 2022).

### 3.2.2. Holocene slopes

In addition to these Pleistocene accumulations, the best-preserved slopes have a Holocene chronology and were named **S2** and **S1**. Both are closer to the current scarp and cover a large extension (Figs. 3, 4b, 4c, 7). The **S2** slopes have thick matrix-supported sediment accumulations mainly formed by silty clay sediments, with angular clasts of limestone and sandstone. The deposit is unsorted, but many clasts are oriented with long-axis downslope. Similar arrangements have been observed in some slopes in Italy and the Maltese Islands (i.e. Hunt et al., 1992). In the past, its longitudinal profile was originally connected with the upper cornice. As the scarp retreated due to erosion, the apex of the talus is unattached. The profile of the S2 slopes and the links of estimated past scarps are represented in several figures (Figs. 4b, 4c, 7, 8b, 8c, and 8d). The distance between the hypothetic **S2** scarp and the present scarp varies highly because the erosive processes are conditioned by many local factors. In general, the obtained values vary between 0 m (where slope **S2** is still attached to the scarp) and 4 m (associated with collapses due to basal piping). The distance varies between 2 and 3 m (Figs. 4b, 4c). The deposits forming slope **S2** can reach 2.5–3 m in thickness with a large amount of fine matrix. After the formation of **S2**, the stream network descending from the scarp incised the deposit, exposing several natural outcrops. In the profiles, the fine fraction was generally eroded, leaving many coarse sediments.

The intensive survey of **S2** slopes revealed 15 sites of geoarchaeological interest associated with the presence of interbedded anthropogenic materials (points LC-0 to LC-15 in Fig. 3). Here we focus on the most chronologically relevant points. On the slopes facing north-northeast and east, the visible natural profiles are scarce (Fig. 8c). However, in point LC-0 (Fig. 9a), a hand mill made from a Permo-Triassic block was found at a depth of 75 cm (Fig. 9b); in outcrops LC-2 and LC-3 (see the latter one in Fig. 9c), several potsherds from the 1st Iron Age were found, which are very similar to those of La Codera site (Fig. 9d). Points LC1 and LC-4 show remains of walls with some Iberian potsherds, which are not completely covered with slope accumulation. Points LC-5 and LC-6 also contain 1st Iron Age potsherds.

Point LC-7, located close to La Codera stream, is different (Fig. 9e). It shows the accumulation of several non-eroded mud plaster fragments (Fig. 9f), many charcoals, and a granite mill. The radiocarbon dating obtained is 2751 ± 21 BP (970–827 cal. BC, 2σ) (sample LC-7 in Table 1). The arrangement implies an *in situ* settlement of the Bronze Age covered with slope **S2**.

The southern and southwestern **S2** slopes are more degraded and the incisions are deeper, exposing thicker talus flatiron deposits (Fig. 8d). Point LC-8 is a stone outcrop associated with the erosion of fine sediments. The lower section of the profile shows potsherds mixed with limestone gravels with the same tilt given their joint transportation (Figs. 10a, 10b). The set also features a hammerstone and charcoal dated to 2848 ± 24 BP (1109–926 cal. BC, 2σ) (sample LC-8 in Table 1), coinciding with the ceramic fragments found and the age of LC-7. In this case, the sedimentary arrangement indicates transportation downhill, suggesting a settlement in the upper section of the slope, probably at the top of La Codera. Points LC-13 and LC-14 are located toward the southwest of La Codera stream, opposite the main archaeological site (Fig. 3). Both points have eroded walls, hammerstone, and non-eroded ceramic fragments lying on the surface due to the erosion of the upper layers of slope **S2** and terrace T2

(Figs. 10c, 10d). These are *in situ* remains of slope occupations. Above point LC-13, eroded ceramic fragments have been dragged from upslope.

There is a terrace-like accumulation on the valley floor (**T2**), formed by silty accumulations, reaching 3–4 m in the lower section at the convergence with the main valley (Figs. 11a, 11b). No ceramic fragments were found in the outcrops since the profile is located in the opposite margin of La Codera archaeological site. However, a deposit of organic matter is interbedded with charcoals in the middle section of the profile (Fig. 11c, sample LC-9 in Table 1). Radiocarbon dating yielded an age of 4121 ± 23 BP (2850–2626 cal. BC 1σ/2865–2577 cal. BC 2σ). As charcoals are not eroded, the deposit lens could be considered part of the Neolithic-Chalcolithic transit. Given its position in the profile, two units can be inferred from the **T2** terrace. The lower section belongs to the **T2a** aggradation phase ending by *ca.* 2900–2600 cal. BC, and the upper section (**T2b**) was deposited after that date. In another profile of the T2 terrace (LC-12 and LC-15), close to the Urnfield site (Fig. 3), the lower part of slope **S2** and the beginning of terrace **T2b** cover the site (Fig. 12a). The stratigraphic arrangement supports the chronology of the upper section of profile LC-9 (Fig. 11c). The mentioned presence of limestone walls, including ceramic fragments in points LC-1 (Fig. 12b) and LC-4, supports the younger chronology of T2b.

Slope **S1** occupies a smaller area and is more developed in the northeastern sector, between the apex of **S2** slopes and the cornice of La Codera archaeological site (Figs. 7, 8c). It also occupies some sectors of the Cerro Norte (Fig. 8e), containing many partially excavated Iberian remains (see locations in Figs. 3 and 6) (Montón, 2020). This archaeological site also occupies the eastern side of the current road, and both sectors are deeply eroded. In two profiles (points LC-10 and LC-11, Fig. 12c), slope **S1** contains many Iberian ceramic fragments and some Medieval *sensu lato*. The fragments were dragged along with the slope sediments. These accumulations also cover part of the Iberian site located at the foot of the Cerro Norte. Thus, they must have come from settlements from Iberian to Medieval times, located on the slope or the top of the hill.

Slope **S1** was also affected by the incision of the stream network, mainly at the foot of the scarps. The sediments were transported to the floor of the main stream of La Codera (**T1** terrace). There are eight small dams on the valley floor located at regular distances (Fig. 3). The dam walls are 1–2 m high and many sediments accumulated behind them. These walls have partially collapsed recently and the sediments are being incised (Fig. 12d).

### 3.3. Anthracology

The anthracological study was based on the charcoal recovered from LC-7, LC-8, and LC-9. The presence of three different plant taxa was documented. Sample LC-9 shows a monospecific composition because the 18 fragments analyzed belong to mastic (*Pistacia lentiscus*). Sample LC-8 is composed of a single charcoal fragment also belonging to mastic wood. Sample LC-7 is composed of two different taxa: Aleppo pine (*Pinus halepensis*) and tamarisk (*Tamarix* sp.). Regarding charcoal taphonomy, most of the fragments analyzed are moderately to strongly affected by the glassy appearance that characterizes the anatomical alteration known in the literature as vitrification (McParland et al., 2010). *Pinus halepensis* is the Mediterranean tree best adapted to drought, withstanding from 1000 mm to 150 mm of annual precipitation. Its main limiting factor is temperature since it does not tolerate an average minimum temperature in the coldest month below -3º C. *Pinus halepensis* grows where the sclerophyllous hardwoods have limited growth capacity, and it prevails over the holm oak in the hyper-xerophilous areas of the Ebro Depression. It appears dispersed over a more or less dense shrubland, without actually defining a forest structure. *P. lentiscus* is a thermophilous Mediterranean shrub with no tolerance to cold. It grows on all types of substrates and is often a part of the shrubland of Aleppo pine and holm oak. It is a plant with many potential uses (wood, leaves, fruits, and resin); therefore it is assumed to have been widely used in ancient times. Tamariks are Mediterranean shrubs belonging to riparian vegetation that grow associated with watercourses. They tolerate soils rich in salts and prefer unstable soils, seasonally waterlogged or subjected to periods of intense evapotranspiration. They are important plants in the riverside landscapes of arid and semi-arid zones (Costa et al., 1997).

## 4. Discussion

The excavations of the archaeological set of La Codera provide data about different occupational phases (from the Bronze Age to the Iberian Epoch). In addition, the geomorphological and geoarchaeological records recovered from the slopes and terraces provide information for the evolutionary reconstruction of La Codera and its surrounding area before, during and after human occupation. The slope accumulations contain records of environmental conditions that promoted their development. The current dry and warm environment favors erosion in the system. Gutiérrez et al. (2010), Oh et al. (2021), and Peña-Monné et al. (2019, 2022) associate this type of slope and, in particular, the formation of talus flatiron with more humid environments, due either to higher rainfall or to a better distribution of seasonal humidity and less evapotranspiration, i.e. cold environmental conditions. Changes in the seasonal distribution of temperature and rainfall have been reported by Baldini et al. (2019) in Holocene records from stalagmites in North Spain.

Two old slope stages (S4 and S3) were identified in the area surrounding La Codera. Stage S4 is furthest away from the caprock, and it is connected with the T4 terrace of the Cinca River. According to OSL datings performed by Sancho (1991) and Lewis et al. (2009), this terrace age is between 39 and 50 ky BP. The S3 slope stage was dated to *ca.* 19-20 ky (Table 1), in agreement with other dates for the same stage in nearby areas (Sancho et al., 1988). The ages of these old stages agree with the glacial maximums of the Pyrenees (Lewis et al., 2009), indicating the wet and cold conditions necessary for the formation of this type of morphology.

The next stage (S2), as well as S1, developed during the Holocene (Peña-Monné et al., 2022). Stage S2 is characterized by its arrangement in talus flatirons and the abundance of archaeological materials. After examination, we inferred that La Codera archaeological site was wider, with a continuous slope starting at the scarp and extending up to the floor of the streams at its foot. In addition, this slope was connected with the lower part of the T2 valley floor infill.

The accumulations of slope S2 show solifluction structures with rock fragments chaotically arranged within a fine matrix. The final regularized morphology is due to this process, probably accompanied by the development of soils and a dense vegetation cover. Although in La Codera it was not possible to identify any soil in this stage, there are descriptions of interstratified soils on S2 slopes in other areas of the central Ebro Basin (Pérez-Lambán et al., 2014, 2018) in residual contemporaneous reliefs. Surface and subsurface runoff with erosion of fine sediments is not appreciable. There seemed to be a perfect ecological balance in which hydric reservoirs were able to maintain the vegetation cover during the dry season, coincident in the Mediterranean climate with the warmer season and high evapotranspiration. The vegetation on the slopes of La Codera, such as albardine (*Lygeum spartium*), must have been adapted to halophilic conditions. At present, this vegetation grows on the northeastern and northern slopes, protecting these slopes even under the current dry conditions. The abundance of detritic limestone fragments in the accumulation must have favored the growth of shrubs and trees like gall oaks (*Quercus faginea*) and junipers (*Juniperus thurifera*).

Despite evolving during the Holocene, S2 formed under environmental conditions similar to those of S4 to S3, but probably less intense. Since the first geoarchaeological studies were performed in the northeast of Spain, both in the Iberian Ranges (Burillo et al., 1981, 1983) and the Ebro Depression (Sancho et al., 1988; Peña Monné and González, 1992; Peña Monné and Rodanés, 1992; Peña Monné et al., 1996; Gutiérrez and Peña Monné, 1998), the climatic genesis of this stage has become evident. In addition, recent research has established the connection between this stage and global climatic changes (Gutiérrez et al., 2010; Pérez-Lambán et al., 2014; Peña-Monné et al., 2019).

The oldest ceramics recovered from S2 slopes are from an *in situ* Bronze Age occupation (LC-7), while the ceramic fragments in LC-8 are part of the slope formation process. There are also Bronze Age ceramics on the slopes of a nearby hill, such as Chalamera (Sancho et al., 1988). Thus, the formation process of slope S2 started during the Bronze Age and continued after the 1st Iron Age because these ceramics are present in most S2 slope accumulations. Given its age, from the paleoenvironmental point of view, slope S2 can be related to the 2.8 Bond Event (Bond et al., 1997) or Cold Phase of the Iron Age. This phase reached its maximum between 2.8-2.5 ky BP.

From an archaeobotanical point of view, tamarisk (*Tamarix* sp.) and Aleppo pine (*Pinus halepensis*), accompanied by rosemary (*Rosmarinus officinalis*), were documented in sample LC-7. They were also the most widely used plants during the occupation of the Iron Age settlement in La Codera, as revealed by the available anthracological data (Vila and Piqué, 2012). Mastic (*Pistacia lentiscus*) was also present although at lower percentages. However, this shrub is the dominant taxon among the sedimented flora in other contemporary settlements in the Lower Cinca River, such as Vincamet (Fraga, Zaragoza), and the Lower Segre River, such as Vilot de Montagut (Alcarràs, Lleida) (Vila and Piqué, 2012). Shrub dominance is the result of intense deforestation, also recorded in the succession of vegetation stages, as revealed by the charcoal analyses carried out in La Codera. This record extends the deforestation area up to the middle section of the Cinca River.

Furthermore, the base of deposit S2 is completely irregular, showing that its sedimentation occurred over a badland developed on the marly Miocene levels (Fig. 13a). In other areas of the Ebro Depression, this erosive morphology developed during the Chalcolithic (*ca.* 4400-4200 BP) (Pérez-Lambán et al., 2014) under drier environmental conditions of the 4.2 Bond Event (Bond et al., 1997). The accumulation of slope S2 regularized this older irregular morphology (Fig. 13b) and reached the valley floor, where the gradient diminished and overlapped with the T2a accumulation, forming the T2b deposit. The carbonaceous sediment (LC-9), dated to *ca.* 2900-2600 cal. BC, is between both units. Few archaeobotanical data are available for the Chalcolithic in the region. Mastic (*Pistacia lentiscus*) is the most widely represented taxon in the archaeobotanical record of the oldest occupation in Roques del Sarró (Segrià, Lleida) (Vila and Piqué, 2012), contemporaneous with sample LC-9, accompanied by rosemary (*Rosmarinus officinalis*), holm oak (evergreen Quercus), and tamarisk (*Tamarix* sp.).

The two oldest slopes of La Codera (S4, S3) are being eroded and have talus flatiron morphologies. Their shape can be identified and reconstructed by the type and composition of the accumulations, partial profile, and position (Figs. 8a and 8b). On slope S2, it is possible to reconstruct the general morphology using a model profile as the criterion. This type of reconstruction was used by Sancho et al. (1988) in Chalamera, where these slopes are better preserved. The morphologies of the talus flatiron of S2 slopes have different degrees of conservation. Their triangular or trapezoidal shape is an intermediate morphology that precedes their erosive degradation and even their disappearance (Fig. 13c). This destructive process may be faster depending on increased gradient, dominant lithologies, orientation, anthropogenic degradation processes, and climate. Erosion reflects the high instability of this type of landform and contrasts with the stability under which slope S2 developed. The erosion process begins at the foot of the cornice, which receives most of the surface runoff from the high areas. The dense drainage disconnects the heads of the slope from the upper scarp, forming gullies that cut the slope deposits up to the base level. Thus, the slope is divided into triangular or trapezoidal segments detached from the scarp-slope-general base level system and evolves isolated (Fig. 7). When the gullies reach the marly-clay substrate, they become entrenched, and the talus flatiron may remain stable for a long time as long as the hardness of the materials and the vegetation cover make it possible. The sediments transported by the gullies formed stage T2b of the valley floor. The upper levels of La Codera contain walls of the Iberian Epoch (Fig. 12b) but the top of the T2 terrace reaches the late Roman Epoch at the regional level (4th–5th centuries AD) (Burillo et al., 1985; Peña Monné, 1996; 2018; Peña-Monné et al., 2000, 2004; Constante et al., 2010; Peña-Monné et al., 2018).

The genesis of the generalized incision process in S2 (Fig. 13c) and the sediment movement toward the valley floor can be difficult to interpret. From a climatic point of view, in Iberian times (2nd Iron Age), at the beginning of the Subatlantic, the climate became temperate (Roman Climate Optimum or Roman Warm Period) (McCormick et al., 2012; Harper and McCormick, 2018) and finally drier toward the end of the Roman Empire (Harper, 2017). At the same time, grazing, agriculture, and forests were overexploited, triggering accelerated morphogenetic processes. In many valleys in the central Ebro Valley, there are thick contemporary accumulations (in many areas higher than 10–15 m), with wood ash and charcoal levels showing great stratigraphic continuity and the dominance of sediments from slope erosion (Constante et al., 2010; Peña-Monné et al., 2018; Peña-Monné and Sampietro-Vattuone, 2019). The anthropogenic effect varies depending on the area, and therefore, it is difficult to identify climatic or anthropogenic signatures. Peña-Monné (2018) considers it to be a consequence of a climate-anthropogenic process. Similar processes, with an anthropogenic origin, have been described in other Mediterranean areas (i.e. Brückner, 1986; Van Andel et al., 1990; Bintliff, 1992; Barker and Hunt, 1995; Hunt, 1998; Butzer, 2005; Fuchs, 2007; Zielhofer et al., 2008; Constante et al., 2010; Bellin et al., 2013; Ackermann et al., 2014).

The T2 accumulations are sediment lags that do not move easily from secondary valleys to the main rivers. However, the records show that at approximately the 7th century AD (Peña Monné, 2018), these accumulations began to erode due to the development of deep incisions powered by piping processes (Peña Monné et al., 2004). This change in the valley dynamics may be related to climate change since there are no evident anthropogenic features. Peña-Monné et al. (2018) related this incision to the 1.4 Bond Event (Bond et al., 1997) and the LALIA (Late Antique Little Ice Age, 530-660 AD) (Büntgen et al., 2016) or Dark Ages Cold Period (DCAP) (Helama et al., 2017). The incision and sediment movement from the small basins remained active during the Medieval Age, climatically the Medieval Climatic Anomaly (MCA).

Stage S1 reflects a new change in the La Codera slope dynamics. Geomorphologically, evidence points to a return to adequate humidity conditions that promote new slope stabilization (Fig. 13d). The best-developed slopes are north- and northeast-facing and usually have more environmental humidity (Fig. 7). These slopes are located between the upper scarps and the apex of the talus flatiron of stage S2 (Figs. 7, 8c). In addition, inside the incisions of T2 accumulations and the valley floors, a new T1 level developed during those times (Fig. 13d). In La Codera, this stage includes ceramic fragments from the Iberian Epoch and Medieval materials; thus, its chronology is post-Medieval. The lack of significant changes in anthropic activity allows us to infer a link with climate change, as in other areas of the Ebro Basin with more precise chronological data. In fact, stage S1 coincides with the Little Ice Age (LIA) (1330-1350 to 1850-1900, Wanner et al., 2011). Oliva et al. (2018) distinguish at least two very cold phases, the first one between 1620 and 1715 AD and the second one between 1760 and 1800 AD in the Iberian Peninsula. Glacial advances were identified in the Pyrenees between 1680 and 1750 AD and between 1890 and 1920 (Serrano and Martín-Moreno, 2018). Saz (2007), based on dendrochronology, showed cold phases between the 17th and 18th centuries. Tejedor et al. (2017) link these cold phases to low solar activity during the second part of the Maunder and Dalton minimums (1790–1830 AD). In addition, the geomorphological evolution of northeastern Spain shows at least two climatic phases characterized by processes promoted by environmental conditions that were cooler and wetter than the current ones (Pérez-Lambán et al., 2014; Peña Monné, 2018; Peña-Monné et al., 2018, 2021).

Finally, both S1 and T1 show degradative processes after LIA, as revealed by active rills on S1 slopes and a new functional incision in T1 infill (Fig. 13e). These processes seem to be linked to the establishment of dryer and warmer conditions since the second half of the 19th century (Modern Warm Period). The dams across the valley bottom were probably built to avoid sediment movement, and once filled, they were also cut by the incision (Fig. 12d). The increasing warm and dry climatic conditions allow us to infer an increase in the erosive processes, mainly surficial and sub-surficial runoff, promoting the erosion of the sediments of S2-T2 stage toward the main fluvial system.

## 5. Conclusions

The archaeological set of La Codera encompasses a long period of human occupation, from the Bronze Age to the Iberian Epoch, with an intense occupation during the 1st Iron Age—the period when the main settlement took place. In addition, the geoarchaeological information of the slopes and valley floors of the surrounding areas complement these data, showing remains of the Bronze Age that were probably originally located on the slopes and the top of the main La Codera settlement. The charcoals interbedded in the T2 Terrace date to *ca*. 2900–2600 cal. BC and suggest human presence even before the Chalcolithic, although settlement remains or artifacts have not been found yet. In addition, the information provided by the archaeobotanical study of samples from the Chalcolithic and Bronze Ages allows us to gain a better understanding of the plant landscape.

The evolutionary model is composed of several stages:

1. Before 2900-2600 cal. BC, the slopes are mainly formed by a badland landscape under arid conditions. The accumulations provide sediments toward the valley floor forming the base of T2 terrace (T2a).

2. Bronze Age and 1st Iron Age occupations. Generation of slope S2 accumulation, regularizing the previous relief. Its age is after the Bronze Age (*ca*. 1100-827 cal. BC) and the 1st Iron Age (*ca.* 7th century BC). The genesis of this accumulation is climatic, contemporaneous with the 2.8 Bond Event (cold phase of the Iron Age). Slope S2 reaches the valley floor and correlates with stage T2b.

3. A subsequent erosion phase produced the cornice-upper slope disconnection and a deep incision of the streams after the Iberian-Roman Epoch. This degradative process was linked to the 1.4 Bond Event, or LALIA.

4. Slope S1 developed during the Little Ice Age. It is the second phase of slope regularization and the formation of a new accumulation on the valley floor (T1).

5. Since the second half of the 19th century, a new erosive phase has affected the S1 and S2 slopes, as well as the T1 floor. This process continues at present.

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## Figure captions

Fig. 1. Location map of La Codera: (a) in the western Mediterranean; (b) in the Iberian Peninsula; (c) in the Cinca valley; and (d) in the geological context of the Ebro Basin.

Fig. 2. Stratigraphic units of the La Codera sector with its main lithological and morphological features and archaeological remains.

Fig. 3. Geomorphological map of La Codera archaeological complex. Location of the archaeological areas and the geoarchaeological sampling points on the slopes and in valley infills.

Fig. 4. Geomorphological cross-sections through the units of La Codera: (a) location and drawing of the cross-sections over the DEM of the sector; (b) cross-section 1-1’ between the upper west platform and the Cinca River; c) cross-section 2-2’ from the Cerro Norte to the upper southern platform.

Fig. 5. Oblique aerial view of La Codera with its surrounding geomorphological units and the location of the floodplain of the Cinca River.

Fig. 6. (a) Location of the archaeological areas of La Codera over an orthoimage from Google Earth (2021); (b) detailed image of the

archaeological structures of the 1st Iron Age archaeological site obtained with sUAV; (c) DEM of the same area showing the topography of the settlement and the buildings of the excavated area.

Fig. 7. Detailed geomorphological map of the platform and slopes of the main archaeological site of La Codera. Based on sUAV orthoimage.

Fig. 8. Slopes of La Codera: (a) slopes (talus flatirons) S3 and S4 between the scarp of La Codera and the Cinca River; (b) slope S3 in the butte near La Codera; (c) slope S2 in the northeast side of La Codera and T2 terrace; (d) S2 slopes and T2 terrace in the southwest side; (e) slopes S2 and S1 of the Cerro Norte.

Fig. 9. Sampling points of slopes S2 located in the NE and E sectors of La Codera: (a) and (b) point LC-0 and detail of the deposit of slope S2 containing a hand mill; (c) and (d) sampling point LC-3 and detail of the ceramic fragments included in the slope; (e) and (f) slopes S2 in point LC-7 and some ceramic fragments. The white points are the dated charcoals (sample LC-8). Red circles show ceramic fragments. The location of these points is shown in Fig. 2.

Fig. 10. Sampling points on the S2 slopes of the S and SW sectors of La Codera: (a) sampling point LC-8 and (b) ceramic fragments in the red circles. The white point shows the position of the dated charcoal (LC-7); (c) remains of a settlement of the 1st Iron Age in point LC-13. The upper part of levels S1-T2; (d) ceramic fragments and hammerstone on the eroded surface of LC-13.

Fig. 11. T2 terraces, S1 slopes, and T1 terraces: (a) general view of the T2 terrace and location of the LC-9 sampling point; (b) and (c) details of the

interbedded charcoal accumulation dated.

Fig. 12. (a) T2 terrace in sampling point LC-12 and relation with the Urnfield site; (b) Iberian Epoch walls in the upper part of the T2 terraces (point LC-1); (c) S1 slopes of the Cerro Norte; red circles with Iberian ceramic fragments.

Fig. 13. Evolutionary model of the La Codera archaeological site surroundings during the Holocene: (a) slopes under intense erosion around the first half of the 3rd millennium BC and formation of the T2a accumulation on the valley floor; (b) S2 slope stabilization stage connected with the valley floor (T2b) during the Final Bronze-1st Iron Age; (c) erosion processes at the top of S2 slopes, cornice retreat, and slope disconnection (talus flatirons development) during the LALIA and Medieval Warm Anomaly (MWA); (e) new aggradation phase on slopes (S1) and alluvial floors (S1) during the Little Ice Age (LIA); (f) erosion and incision over previous accumulations from the Modern Warm Period (MWP) to the present.

Table 1.  14C datings, calibrated with Oxcal v. 4.3 over the IntCal 20 curve (Reimer et al., 2020), expressed with 1σ and 2σ.

Table 2. 14C datings, calibrated with Oxcal v. 4.3 over the IntCal 20 curve (Reimer et al., 2020), expressed with 1σ and 2σ.