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Paleoenvironmental and geoarchaeological reconstruction from late Holocene slope records (Lower Huerva Valley, Ebro Basin, NE Spain)

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ABSTRACT

Slope deposits in semiarid regions are known to be very sensitive environments, especially those that occurred during the minor fluctuations of the late Holocene. In this paper we analyse Holocene colluvium genesis, composition, and paleoenvironmental meaning through the study of slope deposits in NE Spain. Two cumulative slope stages are described during this period. In the study area, both slope accumulations are superimposed and this has enabled an excellent preservation of the aggregative sequence and the paleosols corresponding to stabilisation stages. ^{14}C and TL dating, as well as archaeological remains, provide considerable chronological precision for this sequence. The origin of the accumulation of the lower unit is placed around 4295–4083 cal yr BP/2346–2134 cal yr BC (late Chalcolithic) and it developed until the Iron Age in a cooler and wetter climate (Cold Iron Age). Under favourable conditions, a soil A-horizon was formed on top of this unit. A new slope accumulation was formed during the Little Ice Age. Within the slope two morphogenetic periods ending with A-horizons are distinguished and related with two main cold–wet climatic events. The study of these slopes provides a great amount of data for the paleoenvironmental and geoarchaeological reconstruction of the late Holocene in NE Spain.

Introduction

Colluviums are an important source of information regarding Pleistocene and Holocene sequences and this information can help us understand the paleoenvironmental and genetic processes that have favoured a succession of aggradation and incision stages. Very few dating and geoarchaeological studies have been done in slopes from the late Holocene. This is probably due to three factors. First, the first and main geoarchaeological studies have been done in the eastern Mediterranean, Mesopotamia and Egypt, where these morphologies are scarce. Second, geoarchaeological studies have been centred in other geomorphological records (coastlines, valleys, lakes, aeolian deposits and caves). Third, the gradient of the slopes favour erosion so these are normally residual deposits with issues for preservation. There are many studies of slopes with talus flatiron morphologies in semiarid environments in North America and the Mediterranean region (Gerson, 1982; Schmidt, 1996; Gutiérrez-Elorza et al., 2006, 2010; Boroda et al., 2011). These are generally Pleistocene or early Holocene slopes and so information about late Holocene stages is very limited.

The first geomorphological studies of the Holocene colluviums in NE Spain were made by Burillo et al. (1981) in the Iberian Ranges at heights of over 1000 m asl. These early studies made a first attempt to establish a relation between the observed slope stages and Holocene climatic fluctuations, as well as the importance of anthropic factors in some geomorphic processes.

Geoarchaeological approaches have since been applied in other areas of NE Spain, at lower altitudes, such as the Ebro Depression (100–400 m asl) (Peña-Monné et al., 1996). There are also some works that synthesise the various stages of the Upper Holocene and offer a general evolutionary model (Peña-Monné et al., 2005) of the geomorphological sequence of aggradation and incision processes in the slopes and infilled valleys of NE Spain, and describe their importance for the study of the geoarchaeological record (Gutiérrez-Elorza and Peña-Monné, 1998).

In this study we analyse the slopes of a rocky spur called Peña Enroque, in the Huerva valley. Holocene colluviums, soils, and archaeological remains are well preserved in this relief. Because of

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intense erosion, such a complete assemblage of paleoenvironmental records is exceptional in dry lands. The main aim of this study is to obtain information about the evolution of the late Holocene through the description and analysis of sequences of slope stages at Peña Enroque. Aggradation and incision stages have a particular paleoenvironmental meaning that must be considered when studying the Holocene climate and landscape changes, and these can be correlated to global Holocene environmental trends. Their detailed analysis is of great interest for establishing the relationship between climatic fluctuations and human intervention in the Holocene landscape. In the Mediterranean region, equivalent case studies are not present in the scientific literature.

Moreover, the interdisciplinary methodology used in this study can be applied to other colluviums in semiarid regions in order to improve the paleoenvironmental information of these areas that in some cases lack other sedimentary and morphological records for the late Holocene.

Study area

Peña Enroque is located 4 km to the east of the village of Muel and 25 km to the southwest of Zaragoza (Figs. 1 and 2). This relief is isolated between open plains formed by Pleistocene pediments and fluvial terraces and secondary valleys filled with sedimentary deposits made during the Holocene (known locally as *vales*). The base level of these

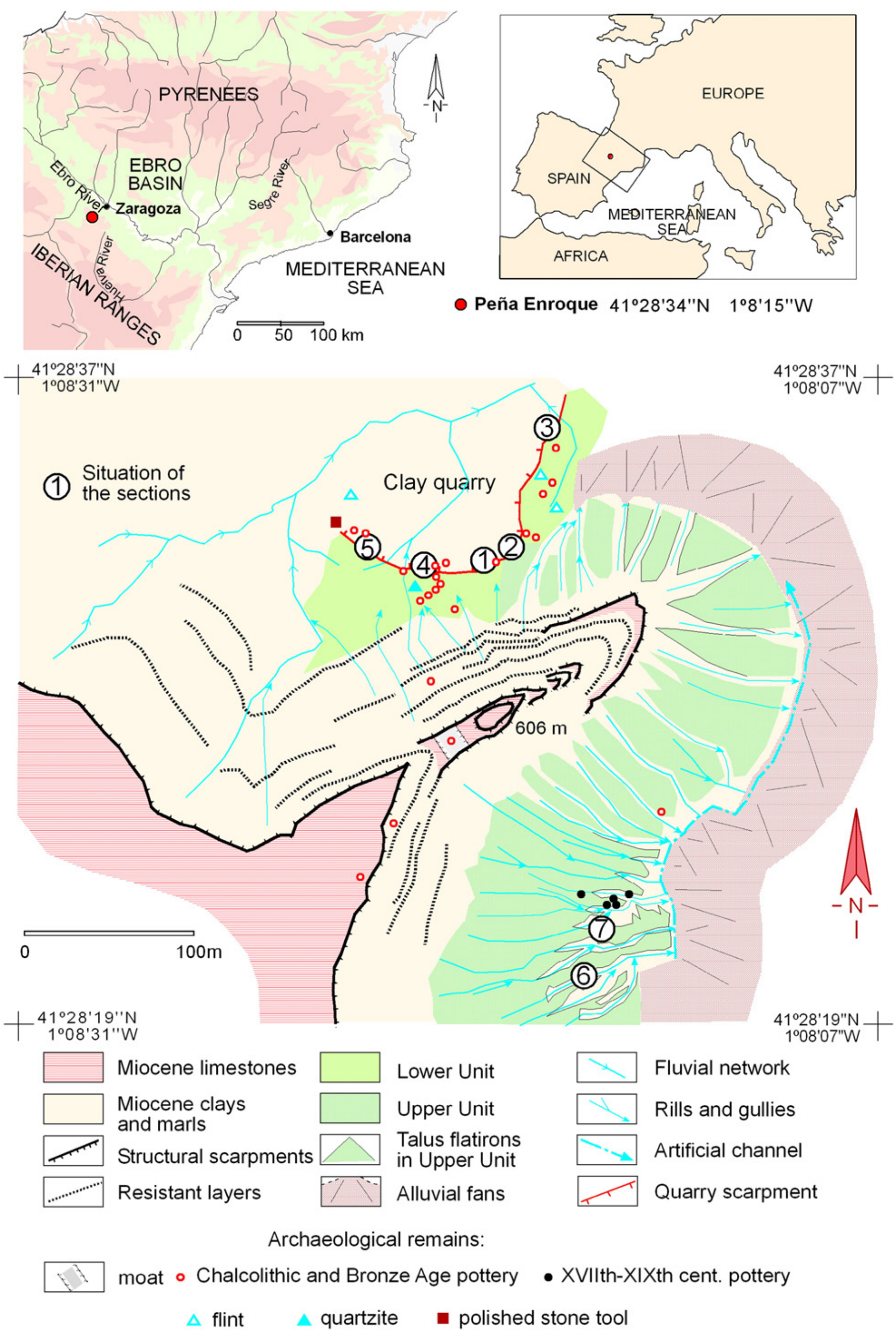

Figure 1. Situation and geomorphologic maps of Peña Enroque, with indication of the seven analysed sections and the location of the archaeological findings.

Figure 2. Panoramic view (from the ENE) of the structural relief called Peña Enroque (606 m asl). The escarpment is ~15 m high. Talus flatirons exposed in the photograph correspond to the upper unit (UpU) of slope stabilisation.

geomorphic features is the river Huerva. This geoarchaeological site is representative of the problems that landscape transformations pose to the study of human occupation in the central sector of the Ebro Depression, especially for the Bronze Age and earlier.

The lower course of the river Huerva is located in the central sector of the Ebro Depression, in NE Spain (Fig. 1). Its upper and middle courses cut through the Iberian Ranges. The river Huerva flows through continental geological formations that were deposited in the Ebro tectonic graben during the Miocene. The main lithologies in the area are lutite, gypsum and limestone—and they maintain their original horizontal arrangement with very few deformations. The resistant upper layers of lacustrine limestone have been modelled into the shape of structural plateaus and mesas (locally called *muelas*), and these are the current outstanding landforms with altitudes over 700 m asl (La Muela, La Plana).

The current climate of this area is Mediterranean–Continental with semiarid features: annual average mean precipitation is ~400 mm. The rain regime is very irregular and there is an intense hydrological deficit (in the nearby observatory at Zaragoza annual mean precipitation is 345 mm and annual mean evapotranspiration is 1200 mm, Cuadrat et al., 2007). In fact, this is the most arid inland region of Europe.

The landscape is characterised by a Mediterranean–Continental halophile and thermophile steppe (*Rosmarinus officinalis*, *Lygeum spartum*, *Artemisia herba-alba*, *Salsola vermiculata*, *Asphodelus sp.*, *Brachypodium retusum*, *Limonium*) on the slopes and rain-fed crop fields on the flat areas (cereals, wines, olives and almonds). This degraded landscape is the result of three main factors: soft lithology, a semiarid climate, and a continuous human occupation that generated an intense deforestation.

Methods

The methods used in this work are designed to bring together data from different disciplines. Initially, we have drawn in detail an evolutionary geomorphologic cartography of the analysed area that describes the aggradation and incision stages of the slopes. Several slope profiles were cleared and drawn to scale, with indication of sedimentary units and levels, as well as information regarding sedimentology, stratigraphy, edaphology, palynology, mineralogy, archaeology and chronology. At the same time, a field survey was made to record the archaeological artefact dispersion on the slope and in the profiles. Two of these sections contained archaeological *in situ* remains and were excavated. Finds have been georeferenced with GPS and drawn on a geomorphologic map (Fig. 1).

To obtain a better control of the chronology of the geomorphological units, we have sampled charcoal findings in four sections for ^{14}C dating in laboratories in *Rijksuniversiteit Groningen* (Netherland) and *Universität Zurich-Irchel* (Switzerland). Two pottery shards were also dated by means of TL dating in the Luminescence Laboratory of the *Universidad Autónoma de Madrid* (Spain).

Furthermore, the sediments in section 6 were sampled using mineralogical and chemical analysis (Geochemistry Laboratory, *Universidad Autónoma de Madrid*, Spain) and edaphological analysis (*Escuela Politécnica de Huesca*, Spain). More precisely, soil organic carbon (SOC) was determined in the fine soil fraction using the wet oxidation method (Nelson and Sommers, 1982) and organic matter was estimated using the van Bemmelen factor (SOC × 1.724). Total carbon was measured using a LECO elemental analyser, and inorganic carbon was estimated by the difference between total and organic carbon and expressed as equivalent calcium carbonate. Electrolytic conductivity (EC) was measured in a 1:1 soil-to-water ratio (Rhoades, 1982). Total phosphorus was calculated by inductively coupled plasma/mass spectrometry (ICP/MS) in a Sciex Elan 6000 Perkin-Elmer spectrometer equipped with an AS91 auto-sampler. Palynological analysis was also performed (*Instituto Pirenaico de Ecología*, *C.S.I.C.*, Spain), but unfortunately the results were negative.

Finally, we have organised the information provided by the different sampling and analysis strategies and we have correlated the results of Peña Enroque with previous studies on the Holocene environmental changes in NE Spain and with paleoclimate events and paleoenvironmental changes in the Mediterranean and North Atlantic regions.

Results

Peña Enroque is a rocky spur (UTM0655526-4593365; 606 m asl) at the extreme of a mesa of Miocene limestone on the western side of the Huerva Valley. It is a long (170 m) and narrow (15–70 m) landform pointing to the NE (Fig. 2). Peña Enroque is formed by a caprock of lacustrine limestone with a 15 m high vertical free face and a talus slope in the lower lutites and marls. This talus gently descends towards the peripheral plains, almost 60 m below the summit. In general terms, the slopes are typically influenced by their orientation in relation to insolation: northern and north-western slopes are more covered by soil and vegetation while south-facing slopes are less protected and therefore more eroded. This asymmetry is due to the differences in water availability and has important consequences for their Holocene evolution.

In this geomorphic area there are two main zones with archaeological material: the top of the spur and the NW slope (Fig. 1). The SE slope also provided some material, but less volume. The summit area is almost flat, and the narrow end is easily isolable because it is surrounded by escarpments around much of its perimeter and the general gradient is 66%. Only the SW flank is accessible. It is, therefore, an ideal defensive position for settlement. There are many similar Bronze Age settlements within a distance of 15 km in the Huerva Valley, such as Los Collados (Jaulín) or San Pablo (Villanueva de Huerva) (Pérez-Lambán et al., 2011; Pérez-Lambán, 2013). The rocky bedrock surfaces in most of the summit area. However, in the centre there is a relic of soil with a few hand-made pottery shards and several ash patches within the bottom remains of an artificial moat that isolated the original settlement site (Fig. 1). One of the potteries (P3) recovered in the moat was dated by the TL method (Table 1) and its age is 3657 ± 250 yr (MADN-5995BIN), that is, the Bronze Age. Similar pottery shards have been recovered within the slope accumulations in the NW sector.

The other area with archaeological remains is the NW slope. Two significant archaeological contexts were found in this sector: a Bell Beaker pottery accumulation in the basal part of the colluvium (Fig. 4, section 4) and a pit excavated in the substratum under the slope (Fig. 4, section 5). Both contexts were dated by ^{14}C analysis of charcoal samples (Table 2). Both dates and potteries belong to the Chalcolithic.

We can assume that occupation began during the Chalcolithic, at least in the NW sector, and continued during the Bronze Age on the summit of the spur. In addition, it must be added that some medieval and modern pottery shards were also recovered in surface findings, but in such small volumes that permanent occupation is not implied.

Two stages of geomorphological slope accumulation were distinguished by means of detailed geomorphological cartography (Fig. 1) and field surveys in Peña Enroque. We denominate the older stage lower unit (LwU), which is mainly visible in the NW sector. However, clay quarrying activities have diminished its original extension. In the SE sector, the LwU is also present, but only under the upper unit. The second stage, the upper unit (UpU), is an accumulation that covers most of the remaining slopes.

The distinction of these two slope colluvium stages is also evident from the study of seven profiles, five of which are in the NW sector (visible in the clay quarry face), and the other two in the SE slope (exhumed by gully incision). These profiles were cleared and cleaned to improve the observation of their stratigraphy. The internal characteristics of these two stages (LwU and UpU) are best shown in the description of the following sections (Figs. 3, 4, 5).

Section 1: 41°28.665′ N, 01°08.226′ W; 546 m asl. Thickness: 270 cm

This profile shows the two aggradation units superimposed one on top of the other (Fig. 3, section 1). They can easily be distinguished by their different colour and texture. The LwU lies on the Miocene bedrock that is composed of lutite and marl. The predepositional morphology of the bedrock is irregular. This lower unit is 110–120 cm thick and is composed of very bioturbated dark clay with angular clasts of limestone and dispersed flint (1). Its dark colour is the result of the remobilization and mixing, by means of solifluction processes, of edaphic remains from the upper part of the slope. Two hand-made pottery shards (belonging either to the Chalcolithic or the Bronze Age) were found in this unit. The main transportation processes were produced by means of slow solifluction which implies a continuous moisturising of the slope, probably because of snow fusion and in the presence of vegetation.

The UpU has an erosive base that shows an unclear lineal contact with the LwU. This is because materials from the highest part of the LwU have been remobilized in the base of the UpU (2a). The base is 116–154 cm thick and its ochre colour is very homogeneous. It is formed by angular limestone gravel and some dispersed flint fragments (2b, 2e). The relative homometry of these materials points towards a physical weathering origin (gelifraction, decompression, dry and wet weathering). The main transportation processes observable in the profile are local fluxes, ploughing blocks, some rill channels (2c, 2d), and the textures of washed fine materials. No artificial evidence was found.

The processes that formed this unit were very different from those that created the LwU. The UpU formation was a gravity-controlled slope where rock falls from the free face were very active and generated large and small blocks that were transported by gravity and rebound. On a slope with little vegetation, hillside surface water runoff due to occasional but intense rainfalls generated a rill wash of fine materials, while solifluction was of lesser importance. UpU is covered by a thin superficial soil (15 cm) shown in the upper part of the profile.

Section 2: 41°28.666′ N, 01°08.221′ W; 542 m asl. Thickness: 214 cm

Only the UpU (1) is visible in this profile (Fig. 3 section 2). It reaches a greater thickness than in section 1 because the LwU lies far below and it is not visible. The unit is composed of several sedimentary layers. Rock falls, fluxes and runoff processes prevail at the 1a level. Above it, several levels of homometric gravel and channel structures (1b, 1f) alternate with more clayey levels with disperse clasts (1c, 1d, 1e). The whole of the UpU has been formed by sediments being dragged through rills and superficial flow processes, with intense fine sediment wash. All this implies a scarce presence of vegetation on the hillside. This section contains no archaeological remains.

Section 3: 41°28.699′ N, 01°08.215′ W; 518 m asl. Thickness: 235 cm

This profile is placed in the lower part of the hillside (Fig. 3, section 3) in contact with the bottom of the valley. It presents almost only LwU, except for some 10 cm in the upper part of the profile. The basal substrate consists of compact Miocene lutite and marl. Above it, there is a 220 cm accumulation of clayey sediment with bioturbation structures, gastropods, and dispersed charcoal fragments. One of these charcoals in the base of level 1b was dated by means of ^{14}C to 4581–4413 cal yr BP/2632–2464 cal yr BC (GrA-47554) (Table 2). There are also some angular limestone clasts and scattered flint fragments.

Section 4: 41°28.659′ N, 01°08.252′ W; 548 m asl. Thickness: 47 cm

The profile in section 4 is placed in the upper part of the clay quarry (Fig. 4). Here the UpU is absent and the LwU is very shallow (20–50 cm). Its composition does not differ from the description of this unit in section 1: dark clays with angular clasts of limestone transported by solifluction processes. In the base there is an erosive channel excavated in the lutite and marl bedrock. Within this channel there was an accumulation of numerous pottery shards corresponding to several vases within an ashen sediment. Some of the pottery shards belong to the Bell Beaker vases (Fig. 4) of the late Chalcolithic. ^{14}C dating of a charcoal resulted in an age of 4295–4083 cal yr BP/2346–2134 cal yr BC (GrA-45131) (Table 2), which is consequent with the typology of the vases. These archaeological remains were recovered almost *in situ*, as can be deduced by the very limited erosion and dispersion shown by

Table 1
TL dating of pottery shards from Peña Enroque.

References	Area & depth (m)	Material	TL age (yr from 2011)	Dates BC/AD	Cultural period
MADN-5995BIN	Summit (0.02)	Ceramic	3657 ± 250	1646 ± 250 BC	Bronze Age
MADN-5998BIN	Section 7 (0.15)	Ceramic	387 ± 21	AD 1624 ± 21	Modern Epoch

TL dating was done in the Laboratorio de Datación de la UAM (Universidad Autónoma de Madrid, Spain), following the methods proposed in Aitken (1985), Fleming (1970), Nambi and Aitken (1986), Zimmerman (1971).

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Table 2
^{14}C dating in slope units from Peña Enroque.

Laboratory reference	Section number & depth (m)	Material	^{14}C yr BP	cal yr BP (2 σ ranges)	cal yr BC (2 σ ranges)	Cultural period
GrA-45131	Section 4 (0.85)	Charcoal	3795 ± 35	4346–4334 (0.8%) **4295–4083 (97.7%)** 4029–4010 (1.5%)	2397–2385 (0.8%) **2346–2134 (97.6%)** 2080–2067 (1.5%)	Late Chalcolithic
GrA-47554	Section 3 (2.05)	Charcoal	4015 ± 40	4781–4769 (1.4%) 4607–4602 (0.5%) **4581–4413 (98.2%)**	2832–2820 (1.4%) 2658–2653 (0.5%) **2632–2464 (98.2%)**	Chalcolithic
GrA-50207	Section 5 (3.1)	Charcoal	4485 ± 35	**5295–5037 (95.3%)** 5007–4979 (4.7%)	**3346–3088 (95.3%)** 3058–3030 (4.7%)	Early Chalcolithic
UZ-5952/ETH-42556	Section 7 (0.95)	Charcoal	2110 ± 30	**2152–1995 (100%)**	**203–46 (100%)**	Ibero-Roman Epoch

Radiocarbon ages were calibrated to 'calendar' ages by using CALIB 6 (Stuiver and Reimer, 1993) based on Reimer et al. (2009) calibration data set. Some conventional ^{14}C dates have multiple intercepts in the calendar yr BP curve. Two-sigma calibrated age (BP and BC) is provided in ranges with indication of their relative area (in %) under 2 σ distribution. Bold font indicates the most likely period.

the shards. This fact and their position on the substratum, in the basal part of the accumulation, implies that the age of this archaeological context can be used as *terminus post quem* for the formation of the slope.

Section 5: 41°28.675′ N, 01°08.303′ W; 537 m asl. Thickness: 336 cm

This is the thickest section. It is placed in the lower part of the hillside, in contact with the valley bottom. In its profile (Fig. 4, section 5) the LwU and UpU are present.

Under the LwU accumulation, the bedrock is irregular and was modified by the excavation of an artificial pit. The infill of this structure (0b) was made of layers of ash and charcoal. ^{14}C dating of a charcoal sample from the ash levels resulted in 5295–5037 cal yr BP/3346–3088 cal yr BC (GrA-50207) (Table 2).

The LwU (1) has several intercalated sub-horizontal levels inside that share their features with those described in other sections. Some dark layers (1f) resembling an A-horizon of a paleosol are the base of the UpU accumulation.

Section 6: 41°28.517′ N, 01°08.192′ W; 536 m asl. Thickness: 250 cm

This is one of two sections located in the gully incisions on the SE hillside (Fig. 1). The basal part of the visible profile is formed of 1 m of the LwU. However, the incision does not reach the Miocene substratum and so the real thickness of this unit remains unknown. At this point, the

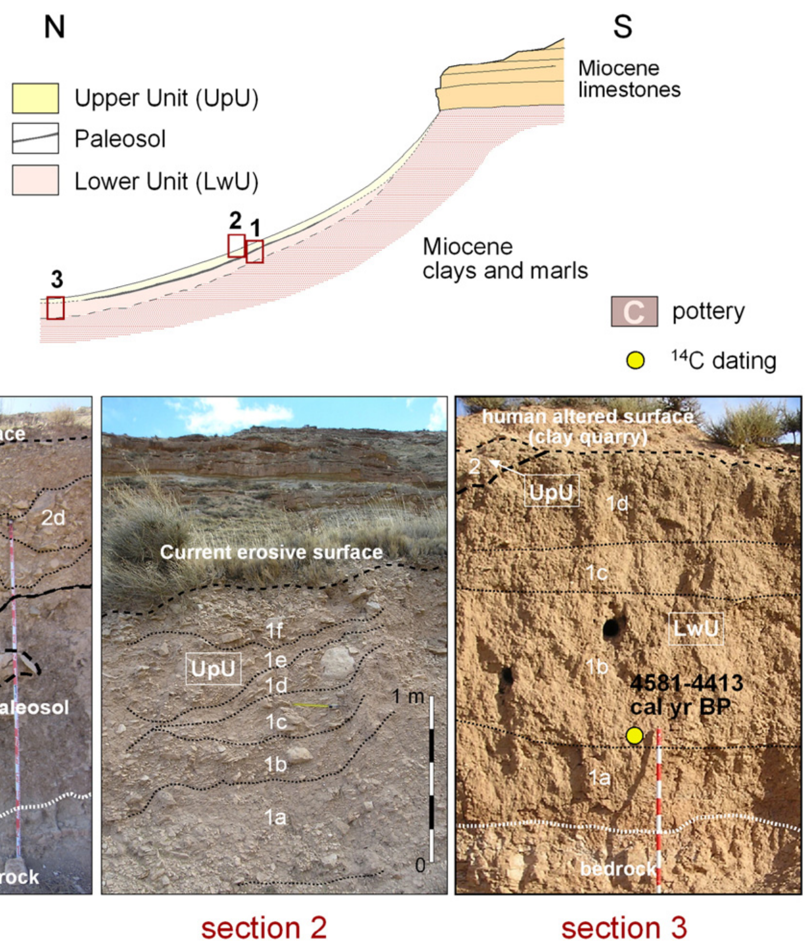

Figure 3. Geomorphologic diagram of the northern slope of Peña Enroque that shows the two described units (lower and upper units), the main paleosol A-horizon, and the position of sections 1, 2 and 3. In the lower part of the figure there are three photographs of the sections with indications of their units and levels, dating samples and archaeological artefacts (see the text for further explanation).

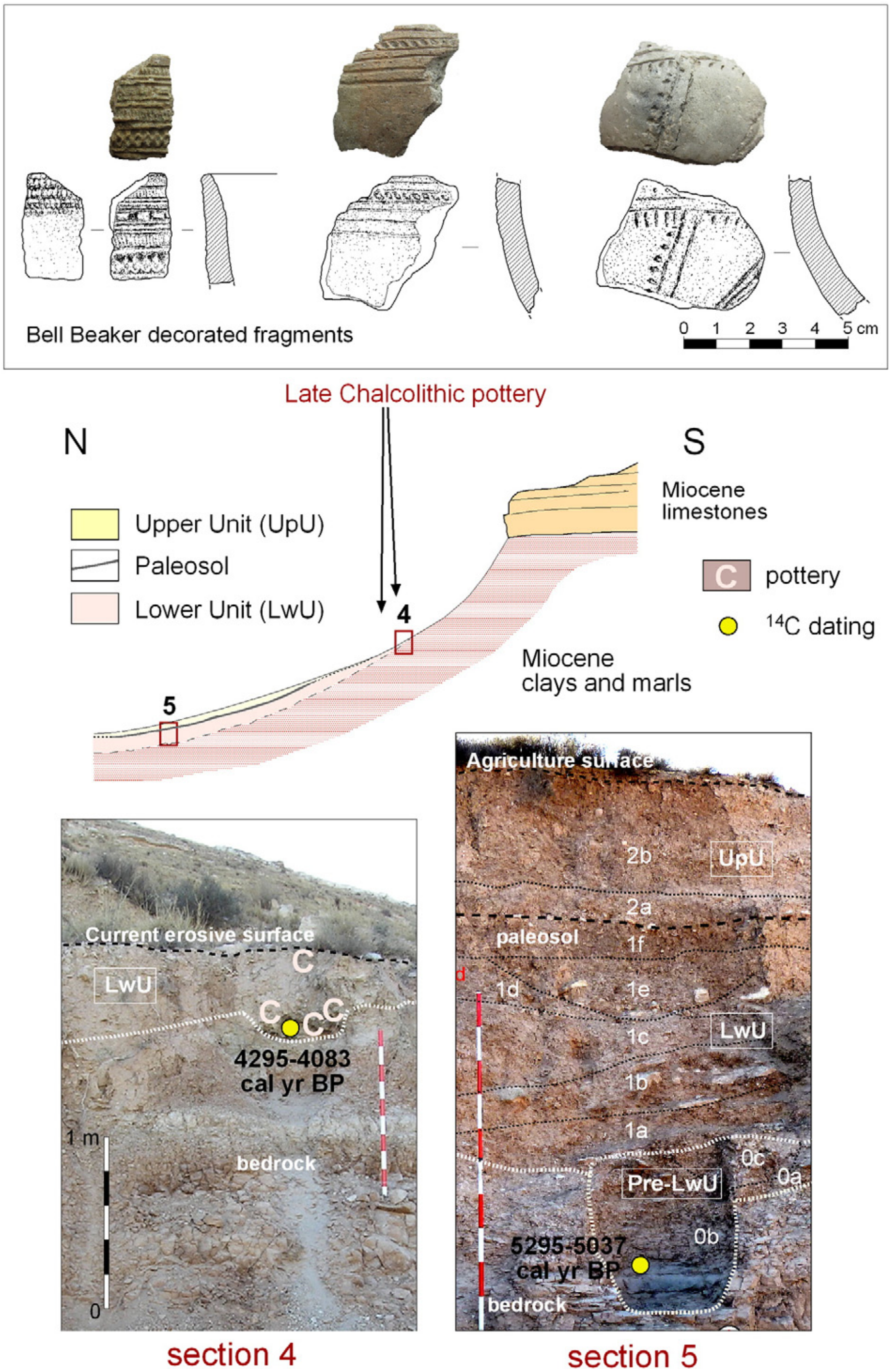

Figure 4. Geomorphologic diagram of the northern slope of Peña Enroque showing the two units (lower and upper units), the main paleosol A-horizon and the positions of sections 4 and 5. In the lower part of the figure there are two photographs of the sections with indications of their units and levels, dating samples and archaeological artefacts (see the text for further explanation). In the upper part, drawings and photographs show some of the Bell Beaker pottery shards recovered from section 4 and surroundings.

LwU is formed of abundant clay and some small gravel (1a). Above the LwU, a 0.25–0.30 m thick A-horizon paleosol has developed (1b, horizon IIIA), perfectly distinguishable because its colour is darker than any other level (Fig. 5, section 6).

Above this paleosol there is a 1 m accumulation of limestone clasts and large blocks in a clayed matrix corresponding to the upper unit. The contact between it and the upper surface of the paleosol is irregular. The UpU is well stratified and the gradient of its levels is higher than that observed in the LwU. In the higher part of the section, there can be observed two slightly darker layers that are equally interpreted as A-horizons from paleosols (2b and 2d, horizons IIA and IAh, respectively). The upper part is cut by the current slope topography (Fig. 6).

No archaeological remains or charcoal samples were recovered in this section. Some charred small roots were found, but these were unsuitable for ^{14}C because their origin was uncertain.

Analysis of paleosols from section 6

In this and the following section, the existence of a preserved continuous paleosol is of great relevance. For this reason, it has been analysed using palynological and edaphological methods. Palynological

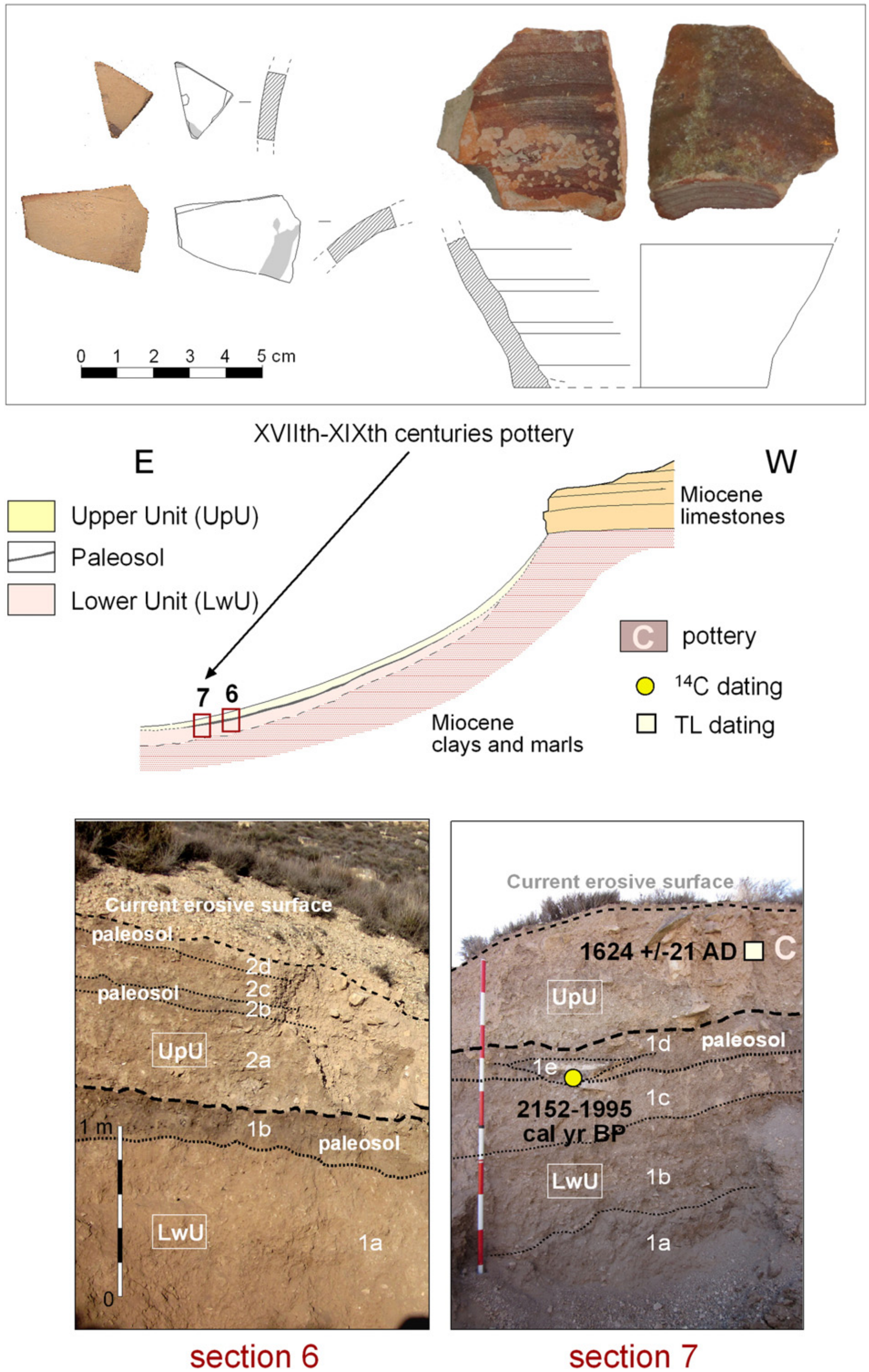

Figure 5. Geomorphologic diagram of the northern slope of Peña Enroque that shows the two described units (lower and upper units), the main paleosol A-horizon and the position of sections 6 and 7. In the lower part of the figure there are two photographs of the sections with indications of their units and levels, dating samples and archaeological artefacts (see the text for further explanation). In the upper part, drawings and photographs represent some of the Modern Age pottery shards recovered from Section 7 and surroundings.

analysis gave negative results because the pollen was too poorly preserved and the pollen count was not statistically representative. Physical and chemical properties of the soil (Table 3) were much more informative.

In the soil that was sampled (section 6), successive discontinuities were observed through the presence of stone lines and the heterogeneous distribution of particles, in both gravel (>2 mm of diameter) and fine earth (<2 mm) fractions. The rock fragments are Miocene limestones, mainly fine and medium gravel (2–60 mm; occasional boulders of 200–600 mm in IIC2), angular shaped, and fresh or slightly weathered; the content being higher in the first two profile metres. For all horizons, the particle size distribution is dominated by clay and silt fractions.

In addition to the sub-current IAh horizon (profile level 2d), two buried horizons (IIA, profile level 2b, 90–110 cm deep, and IIIA, profile level 1b, 170–200 cm deep) were found. These A-horizons have an organic matter content of about 4%, a C/N ratio of between 18 and 30, and phosphorus content from 200 to 280 mg/kg—in all cases higher

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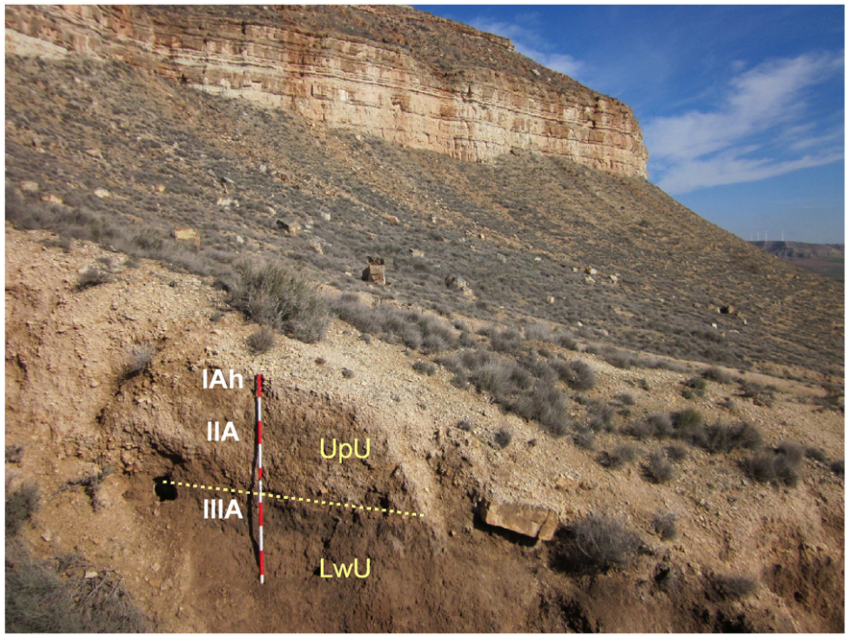

Figure 6. Photograph of the SE side of Peña Enroque showing the Miocene limestone escarpment and the slope of the upper unit. In the cut of the gully, the two superimposed units can be observed. A-horizons of the paleosols are indicated.

values than the underlying B or C-horizons. Moreover, A-horizons have a lower Munsell value (inversely related to soil organic matter); as well as lower soluble salt (EC) and calcium carbonate contents than their respective underlying horizons. These chemical and physical properties show that the soil (and therefore, the aggradation process) had two periods of stability, when more soluble salts were washed away and fresh organic matter and some major nutrients such as phosphorus were accumulated on the A-horizon surfaces.

The sub-current paleosol (IAh–IC) and the intermediate paleosol (IIA–IIC) are classified as *Haplic Regosol* (*calcaric*, *skeletic*) for IUSS (IUSS Working Group WRB, 2007). The third buried paleosol is also an *Haplic Regosol*, but shows a slightly larger development (IIIA–IIIBw–IIIC), which could have evolved to *Haplic Calcisol*, according to the soil chronosequences studied in these semiarid environments (Badía-Villas et al., 2009). There are very weakly developed mineral soils that are deep, well drained, and derived from unconsolidated materials. Regosols correlate with *sols peu évolués régosoliques d'érosion* (Baize and Girard, 2009) or Entisols (Soil Survey Staff, 2010).

Section 7: 41°28.534′ N, 01°08.193′ W; 531 m asl. Thickness: 238 cm

This section is similar to the previous section. Some 130 cm of LwU is seen (Fig. 5). The upper part of this unit (1d) is formed of a 25–35 cm thick dark layer (level 1d in section 7) that corresponds to IIIA-horizon in section 6 and is present in all incisions in the SE sector of Peña Enroque. Inside this A-horizon there is a small groove (45 cm wide and 12 cm deep) that contains a considerable amount of organic material, ashes from a hearth, and a few charcoal fragments. ^{14}C dating of one of these fragments gave the date of 2152–1995 cal yr BP/203–46 cal yr BC (UZ-5952/ETH-42556) (Table 2). The upper part of this hearth is covered by a limestone slab severely altered by fire. This

Table 3
Main soil characteristics analysed in section 6.

Geom. level	Sample depth (cm)	Edaf. horizon	Munsell colour notation (dry; wet)	Gravels (% w/w)	Organic matter (%)	C/N ratio	Total P (mg/kg)	CE (dS/m)	$CaCO_3$ eq (%)	Texture
2d	15	IAh	7.5 YR 6/3; 7.5 YR 5/3	44.3	3.64	30.1	200	0.43	55.3	Clayey-skeletal
2c	45	IC1	7.5 YR 6.5/3; 5.5 YR 5.5/3	70.3	1.99	9.6	109	0.92	43.1	Clayey-skeletal
	65	IC2	7.5 YR 6.5/3; 7.5 YR 5/3	57	1.48	4.5	144	2.92	61.3	Clayey-skeletal
2b	100	IIA	7.5 YR 6/3; 7.5 YR 5/3	39	4.63	17.9	198	0.75	37.0	Clayey-skeletal
2a	120	IIC1	7.5 YR 7/3; 7.5 YR 6/3	23	1.84	7.1	165	4.34	49.3	Clayey-skeletal
	160	IIC2	7.5 YR 6.5/3; 7.5 YR 5/3	72*	2.03	9.0	151	nd	43.3	Clayey-skeletal
1b	185	IIIA	7.5 YR 5/2; 7.5 YR 4/2	35	4.00	18.0	279	0.34	34.5	Clayey
1a	210	IIIBw	7.5 YR 6.5/3; 7.5 YR 5/4	8	2.26	11.9	213	1.03	41.2	Loamy
	270	IIIC1	7.5 YR 6.5/3; 7.5 YR 5/4	22	2.27	10.1	212	0.71	41.7	Clayey
	330	IIIC2	7.5 YR 6.5/3; 7.5 YR 5/4	23	2.26	8.7	222	1.15	41.5	Clayey

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paleosol equals that described in section 6, although in this case it can be termed *Technic Calcisol* because of its important anthropic traces.

On top of the paleosol, the UpU (2) is 75 cm thick and its characteristics are very similar to those described in section 6. In the upper part of this section three pottery shards were recovered. Their typology belongs to the 17th to 19th centuries. One of them was also dated by means of TL to 387 ± 21 yr (MADN-5998BIN) (Table 1), that is, 17th century.

Discussion

From the information obtained through the study of the seven sections we can establish the series of evolutionary stages at Peña Enroque (Fig. 7). This sequence can be related to the different Holocene climate periods and human occupation phases.

The pre-lower unit (Pre-LwU)

As stated previously, sections 1 and 4 show a very irregular erosive contact between the substratum and the LwU. This is evidence of the existence of an actively erosive stage previous to the LwU (Pre-LwU). During this stage, the landscape would have been characterised by the presence of widespread gullies and rills, producing extensive badlands on the Miocene clay and marls. Section 5 shows the artificial excavation of a pit in a thin accumulative level (Fig. 4, section 5, level 0a) with clayey substratum, that is in a mainly erosive area (Figs. 7, 1 and 8).

The date (Pre-LwU) can be chronologically placed thanks to the existing ^{14}C dating (5295–5037 cal yr BP/3346–3088 cal yr BC, GrA-50207) from the artificial pit. This date falls between two chrono-cultural periods: the end of the Neolithic (5500–2700 BC) and the beginning of the Chalcolithic (2700–2100 BC). Moreover, this Pre-LwU

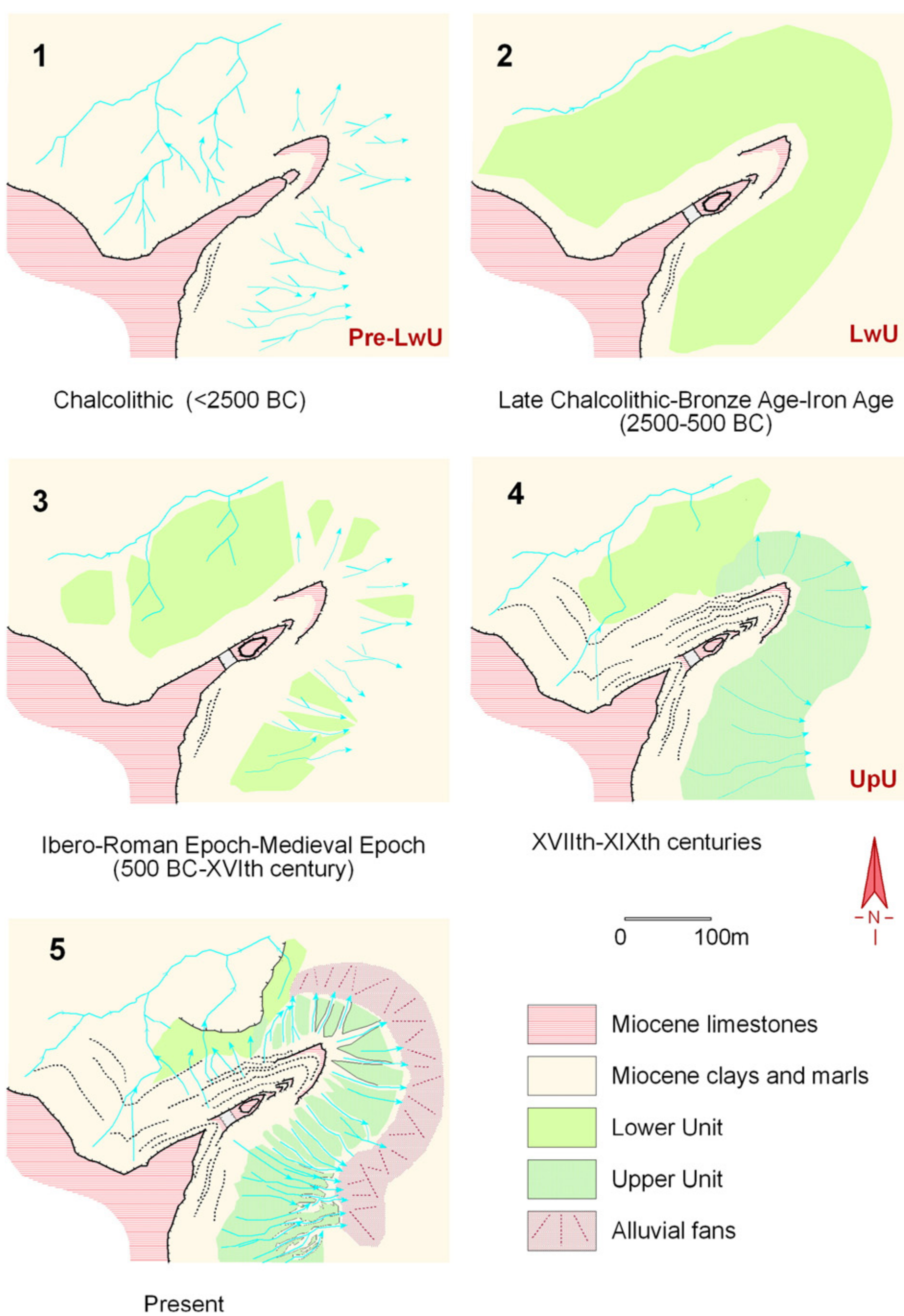

Figure 7. Evolutionary diagrams showing the geomorphological state of Peña Enroque during different stages—from the Chalcolithic to the current morphology (2700 BC–AD 2013). The moments of aggradation of the two slope units are evidenced.

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must be previous to the important accumulations of the LwU, whose base dates are between 4581–4413 cal yr BP/2632–2464 cal yr BC (GrA-47554) (section 3) and 4295–4083 cal yr BP/2346–2134 cal yr BC (GrA-45131) (section 4) or the late Chalcolithic.

From the paleoenvironmental point of view, Jalut et al. (2000) indicate that the Mediterranean region was experiencing a dry stage in the Pre-LwU phase, coherently with the aridity generated in Southern Europe and the Near East during the 4.2 cal ka BP event (Bond et al., 1997). The RCC (rapid climate change) established by Mayewski et al. (2004) for 4200–3800 BP would also coincide with this dry environment stage (Fig. 9). We can deduce a climate with scarce but concentrated precipitations (similar to the current pattern) that would prevent the accumulation and stabilisation of slopes and would favour the incision of gullies and rills. This erosive stage must have been widespread across NE Spain, since slopes of this or previous periods have never been found. The only exceptions are some rarely preserved much older slope formations from the Pleistocene and early Holocene (Gutiérrez-Elorza et al., 2006, 2010). At the same time, since the Neolithic (5500–2700 BC) the tributary valleys in the region underwent an aggradation process that evidences an increase in erosion in the slopes of the tributary basins of the river Huerva, and reaching high erosion rates before the Bronze Age (Peña-Monné et al., 1993, 2001, 2004; Constante et al., 2010, 2011).

In NE Spain there are no other descriptions of evidence of this Pre-LwU erosive stage. However, its existence was suggested in Burillo et al. (1981) and Gutiérrez-Elorza and Peña-Monné (1998) as a result of the observation of erosive morphologies previous to the LwU, and termed the *Post-Bronze Age Slope*.

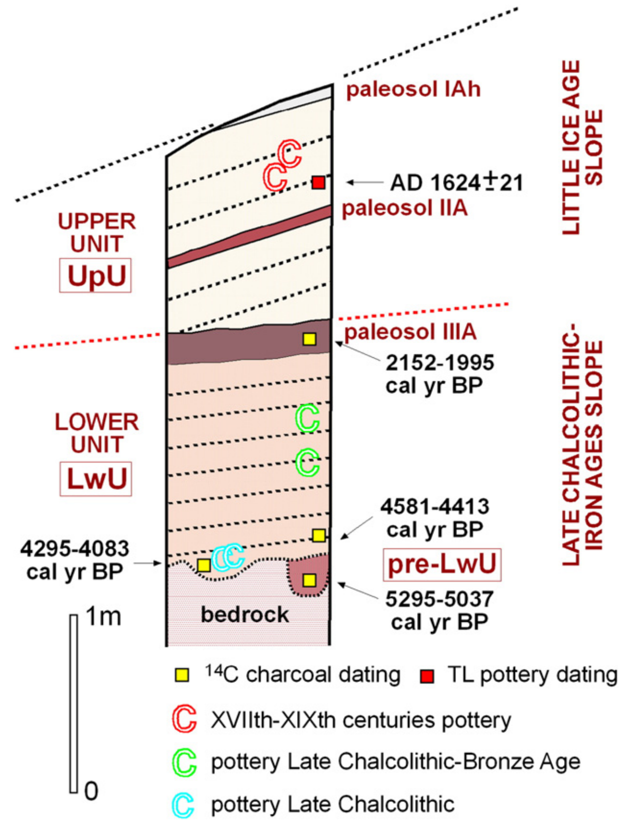

Figure 8. Diagram synthesising the data obtained from the seven analysed sections. The arrangement of the two slope units, the paleosols, pottery position and chronological data are shown.

The lower unit (LwU)

The study of the slopes of Peña Enroque revealed an abrupt change from the late Chalcolithic. The new prevailing process is a large aggradation dynamic in the slopes that is visible both in the cartography (Fig. 1) and in the profiles of the sections (Figs. 3, 4, and 5).

The LwU accumulated on a paleorelief of irregular morphology and generated a complete superficial stabilisation by means of a long-lasting accumulative process. Pottery shards in the base of this unit (section 4) and the ^{14}C dates of the lower levels in sections 3 and 4 indicate the initial moment of the sedimentation of the slope (Fig. 8). It is interesting to highlight that in section 4, the dates belong to pottery and charcoal which were found *in situ* or just slightly displaced. This circumstance gives great precision to the identification of the beginning of the aggradation (4295–4083 cal yr BP/2346–2134 cal yr BC, GrA-45131). However, the dating in 4581–4413 cal yr BP/2632–2464 cal yr BC (GrA-47554) in the base of section 3 must be considered the least precise *post-quem* date, as it was performed on a charcoal that was much displaced as a result of the slope processes. Therefore, the beginning of this regularising stage must be approximately placed in the late Chalcolithic, around 4295–4083 cal yr BP/2346–2134 cal yr BC (GrA-45131). This meant that for the first time the starting point of the LwU had been determined with precision. In previous studies of other slopes in the Iberian Ranges (Picazo-Millán, 1999–2000) Chalcolithic findings and ^{14}C dates were not obtained from an *in situ* context, so their precision was less reliable.

Pottery shards from the Chalcolithic or the Bronze Age (2500–1500 BC) found within the LwU (section 1) indicate that the slope formation continues after their chronology.

Except for the abovementioned pottery, in Peña Enroque we lack dating evidence for the upper levels of the LwU. However, in other slopes in NE Spain, the development of this accumulation stage has been observed during the Bronze Age (Burillo et al., 1981; Peña-Monné et al., 1996) and the Iron Age (Picazo-Millán, 1999–2000; Gutiérrez-Elorza et al., 2010). Iberian (>500 BC) or later remains are always located above these slopes acting as *terminus ante-quem*.

Therefore, we can conclude that the formation of the LwU spans from 4295–4083 cal yr BP/2346–2134 cal yr BC (GrA-45131) to 700–550 BC, resulting in a generalised stabilisation of the slopes (Figs. 7, 2).

An important aspect of the evolution of the LwU is the development of an A-horizon (sections 1, 5, 6 and 7) preserved thanks to the superposition of the later UpU. The date obtained from an *in situ* charcoal of a hearth inside the A-horizon from the paleosol in section 7 is 2152–1995 cal yr BP/203–46 cal yr BC (UZ-5952/ETH-42556). This signifies that its edaphic development reaches at least the Ibero-Roman Period.

The characteristics of the paleosol in section 6, especially its 1b level (horizon IIIA, Table 3), make it clear that it was formed in a stable stage which was long enough to allow the formation of a B-horizon and achieve a low salt content and a high concentration of organic material and phosphorus. From a physical and chemical point of view, the IIIA horizon has the highest productivity potential of all the analysed edaphic horizons in the profile in section 6. Its organic matter, nitrogen, and phosphorous values are higher than the values of the other two A-horizons (IIA and IAh). Its granulometric composition and well structured thick horizons (Bw) favour a greater water reservoir capacity and it contains evidence of intense biological activity. These hydrologic and biotic characteristics of the IIIA horizon reinforce its interest as a potentially productive soil. However, no evidence of anthropic use was found in this paleosol. The most frequently used chemical indicators of anthropic intervention on the soils are N, K, P, Ca, Mg, organic matter and pH (Leonardi et al., 1999). Of these, Ca and Mg are not very significant in dry limestone environments, and there is little doubt that the most important is phosphorous (Eidt, 1977; Schlezinger and Howes, 2000). P levels in horizon IIIA in the profile in section 6, as well as the other indicated parameters, are lower than what is normally registered in human used paleosols in semiarid environments (Sampietro et al.,

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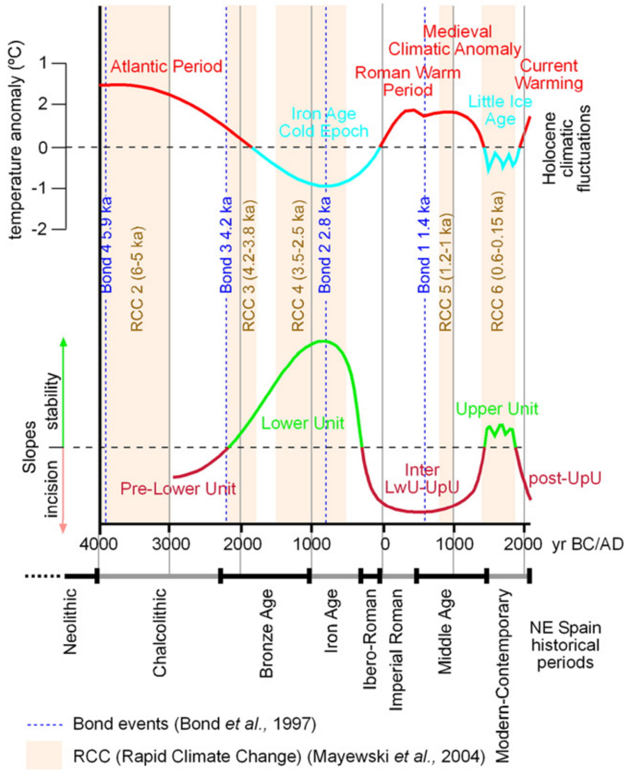

Figure 9. Graph relating the described stability/incision slope stages to the climatic evolution of the late Holocene, the Bond et al. (1997) events, the Mayewski et al. (2004) RCCs (rapid climate changes), and the historical periods from the late Neolithic to the current time.

2011). Therefore we must assume that the surface of this paleosol in Peña Enroque was never used for anthropic activities. This circumstance can explain why it was so well preserved and active (as it was protected by undisturbed vegetation) until Roman times. In addition to the lack of evidence of anthropic use of the paleosol in the analysed profile, the fact of its existence is of great importance as it demonstrates the presence of productive soils for agriculture and cattle in this region until the Roman times.

The prevalence of solifluction processes, with an abundance of clay, can be related to humid conditions. Gutiérrez-Elorza and Peña-Monné (1998) argued that the slopes of this stage are the result of a regime of precipitations that were not very intense—so preventing drain concentration while favouring water infiltration. Paleoenvironmental reconstructions of the Upper Holocene comprise cold and humid conditions for the Bronze and Iron Ages on a global scale (Lamb, 1977) and in the Mediterranean region (Bintliff, 1982). This moment coincides with Iron Cold Age (Gribbin and Lamb, 1978), in the transition between the Subboreal and the Subatlantic. This could be enough to favour higher rates of winter snowfall and, therefore, the presence of melt water that moisturises the slopes. The relationship of these slopes with a climate which was cooler than today was already determined in the very first geoarchaeological studies of Holocene slopes (Burillo et al., 1981). This relation has also been used to explain Pleistocene slope accumulations in the N and NE of Spain (Sancho-Marcén et al., 1988; Gutiérrez-Elorza et al., 1998, 2006, 2010) that share similarities with respect to their genetic processes.

For the Upper Holocene this stage matches with the 2.8 cal ka BP event of Bond et al. (1997) or the 2.6 cal ka BP event of Van Geel et al. (1996), who place the climax of this cooling stage around 800–600 BC. Moreover, the RCC (rapid climate change) pointed out by Mayewski et al. (2004) between 3500 and 2500 cal yr BP on the basis of GISP2 and other indicators covers the chronology of the formation of the LwU slopes in the Huerva Valley (Fig. 9). Additionally, the existence of humid conditions for this chronological period in a closer area can be observed in the data regarding paleofloods in Spain provided by Thorndycraft and Benito (2006) and Benito et al. (2008), or in the high lake levels in the central sector of the Ebro Basin (Gutiérrez et al., 2013) and the Pyrenees (Corella et al., 2011a,b). Moreover, the aggradation in the Holocene infills of the valleys near Peña Enroque evidences an environment that was wetter than today (Peña-Monné et al., 2004; Sancho-Marcén et al., 2008; Constante et al., 2010).

Erosive stage between LwU and UpU (Inter LwU-UpU)

Slopes of the LwU were partially removed by an erosive stage after the Bronze and Iron Ages, but before the formation of the UpU (Figs. 7, 3).

In previous studies concerning this sector of the Huerva and the Ebro valleys, the beginning of this erosive stage was placed in the Ibero-Roman period. This stage generated important accumulative infills in the nearby valley bottoms (Peña-Monné et al., 2004; Constante et al., 2010, 2011). The characteristic dynamics inferred from the sediments in these valleys match with climate conditions similar to the present day: short, intense, and frequently stormy precipitations that favoured the formation of gullies. In addition to the climatic cause, it is necessary to consider the action of a major human intervention in the landscape that is characteristic in this region following the Iberian period and especially during the Imperial Roman times (as registered in the valley infills). These sediments have a prevalence of fine-grained materials that come from the washing of the soils of the slopes and they contain continuous charcoal levels as a result of generalised deforestation (Peña-Monné et al., 2004; Constante and Peña-Monné, 2009).

This erosion also led to the re-activation of the escarpment retreat processes by means of basal sapping, lateral decompression of limestone free faces, and rock falls. This would have affected the settlements placed on the hilltops and platforms, as they would lose much of their surface and perimeter.

Chronologically, this erosive stage must be placed after the LwU and before the new slope generated during the LIA, that is, in a chronological range that includes the Ibero-Roman period and the Middle Ages, without the possibility of further precision, at least for the moment (Fig. 9). Environmental conditions related to this stage are found in the Warm Roman and Medieval Periods and completely described in paleoclimatic literature (Maasch et al., 2005). Jalut et al. (2000) point out two phases of increased aridity in the Western Mediterranean during this temporal *lapsus*. Moreno et al. (2012) gather information about the influence of the Warm Medieval Period – the Medieval Climate Anomaly – in the evolution of the palynological lake and marine records in the Iberian Peninsula. These records show a prevalence of xerophytic and heliophytic taxas between AD 900 and 1300 in the Mediterranean area—in contrast with the more humid north of Spain. Similarly, in Roberts et al. (2008, 2012) there is contrasting palaeolimnological data concerning the humidity of the western (dryer) and the eastern Mediterranean (wetter). Finally, this stage is placed between the RCC 4 and 6 events of Mayewski et al. (2004), with a cooler interruption in RCC 5 (1200–1000 cal yr BP).

As a consequence of this erosive stage, the LwU has disappeared almost completely in many areas of the Ebro Depression. Southern slopes are severely eroded, while northern slopes preserve part of the LwU regularisation.

The upper unit (UpU)

The previous erosive stage generated a severely degraded and irregular landscape, somewhat similar to the Pre-LwU, but without the complete disappearance of the former slope accumulations. The normal trend is for new accumulations of the UpU to progressively substitute the LwU. However, Peña Enroque has a different arrangement of the slopes: the UpU is superimposed on the LwU in many

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areas (sections 1, 3, 5, 6 and 7). This circumstance has very positive consequences for the study of the evolutionary stages of the slope, because the LwU and its paleosol are preserved almost intact (Fig. 8).

This second stage of slope stabilisation differs from the LwU. The morphology of the new slopes is steeper (30–35°), begins at the foot of the limestone escarpment, and has a concave profile that connects with nearby valleys. We can observe this stage as an independent landform in the N, S and SE of Peña Enroque (Fig. 2).

The composition of the UpU shows a prevalence of thick sediments, even including boulders and cobbles. It is a debris-covered and gravity-controlled slope with rock falls, washing of fine materials, localised fluxes, ploughing blocks, etc. These materials and processes fit in a dynamic of limestone escarpment retreat and transport by means of surface run-off and generation of debris fans in a steep slope setting. The final result is stabilisation, but not as complete as it was with the LwU. Now the slopes have two sectors with morphologies that are clearly separated: an almost vertical escarpment and a concave or rectilinear talus (Figs. 7, 4).

Inside the accumulation of the UpU there are at least two moments of increased stability indicated by the development of two paleosols with A-horizons (IIA and IAh, levels 2b and 2d in section 6, respectively) that break the accumulative dynamic (Fig. 5, section 6, and Fig. 8). Horizon IAh is considered a paleosol and not the current active soil because it is being cut by the existing erosive slope profile (Fig. 8). These two paleosols were quickly generated without time to develop B horizons and in the case of IAh almost without any washing of salts. The short time duration of these sub-stages of the UpU is confirmed by the chronology obtained in sections 6 and 7.

The only chronological elements for the UpU are five modern wheel-thrown pottery shards recovered from the upper levels of this unit in section 7, providing a *post-quem terminus* for the formation of the deposit. Their typology points to the 17th to 19th centuries and TL dating performed on one of them precisely confirms that chronology to AD 1624 $\pm$ 21 (MADN-5998BIN). This age for the UpU accumulation fits with the chronology of other slopes in nearby areas of the Ebro Depression, such as the northern escarpment of the river Ebro at El Castellar and Castillo de Miranda (Peña-Monné, 1996; Constante et al., 2010) or in the lower courses of the Segre and Cinca Rivers (Peña-Monné et al., 1996). Therefore, we can assume that it is a generalised slope formation stage in NE Spain. The climatic conditions that were necessary for its genesis imply an abrupt change that contrasts with the previous stage characterised by erosive processes. However, this new stabilisation stage represented by the UpU was less important than the LwU.

There is only one climatic phase after the Medieval Climate Anomaly with the specific conditions that could generate the UpU, that is, the LIA with its highly variable precipitation regime (Fig. 9). In addition to the UpU, the LIA is also responsible for several aggradation stages in the bottoms of the secondary valleys (Peña-Monné et al., 2001; Constante et al., 2010) and important flood episodes in the main courses of NE Spain (Llasat et al., 2005; Thorndycraft and Benito, 2006; Benito et al., 2008) and Europe (Macklin et al., 2006). The wetter conditions of the LIA are also evidenced by the palaeolimnological records in the western Mediterranean – Estanya and Montcortés lakes (Corella et al., 2011b; Morellón et al., 2011) – in contrast with the eastern Mediterranean that was dryer during this period (Roberts et al., 2008, 2012).

The two sub-stages of the UpU represented by the horizons IAh and IIA show the environmental variability of the LIA, which has been determined for the NE of Spain through dendroclimatic studies (Saz-Sánchez, 2003) and Pyrenean glacial evolution (Chueca and Julián, 1996). These types of paleoclimatic records, as well as other paleoclimatic records (lacustrine and marine sequences, increased runoff, vegetation changes) enable the determination for the Pyrenean region (Morellón et al., 2012) of two stages in the evolution of LIA: the first with fluctuating moist conditions and relatively cold temperatures (ca. AD 1300–1600); and the second with lower temperatures (glaciers advances), greater runoff, and more humidity (ca. AD 1600–1800). This climatic information concurs with the data obtained from the UpU in section 6. The pottery shard dated by means of TL in section 7 was placed slightly above the horizon IIA. Therefore, the first LIA accumulation and later stabilisation took place before the 17th century. During or after this century, the second accumulation arose (Fig. 5, section 6 level 2c, Table 3 C1 and C2 horizons) and so the accumulation could be related to the cooler temperatures of the Maunder Minimum (AD 1640–1710). In NE Spain, dendroclimatic data shows a series of dry anomalies (AD 1660–1670, 1680–1690, Saz-Sánchez, 2003) during this second period. It is not until the end of the 19th century that we find a recovery of precipitation (AD 1880–1890, Saz-Sánchez, 2003; Morellón et al., 2012) which can be linked to the development of the IAh horizon. Its short temporal duration and its proximity to present day dry conditions concur with the poor development of this paleosol as evidenced by the edaphological data. These stages during the LIA are concurrent with the successive solar irradiance minimums described by Steinhilber et al. (2012) by means of different proxy data.

Present dynamics

In recent times, the prevailing processes in these slopes are mainly incisions in the UpU unit. In those areas where both units are superimposed (sections 1, 5, 6 and 7) the incisions cut through the whole of the accumulation. These gullies have a radial course from the base line of the limestone escarpment towards the nearby flat fields and they generate talus flatiron morphologies in the slopes (Figs. 7, 5) and alluvial fans in the distal segment.

From the second half of the 19th century, climate conditions favoured the dynamism of the erosive processes. Continental Mediterranean climate has few, but very intense precipitations, that are especially erosive during the summer. Despite a recent decline in anthropic land use pressure, the intense degradation of the natural environment caused by several centuries of overgrazing on the slopes and the soft local lithologies (gypsum, clay and marl) further promoted erosive processes because they prevented vegetation recovery.

Conclusions

The information obtained through the geomorphological and geoarchaeological study of Peña Enroque enables us to make more precise descriptions of some aspects of the Holocene paleoenvironment in NE Spain. The quick response of the slopes before abrupt changes in semiarid regions generates morphological and sedimentary records that are an important source of environmental information, including edaphological, geomorphological, geoarchaeological, and sedimentological data. Results from the study of these records correlate very well with other paleoenvironmental proxies (limnological, paleofloods, palinological and glaciological data).

The existence of two main slope stabilisation stages during the Upper Holocene has been demonstrated and described with detail. The LwU (Late Chalcolithic–Roman Age) was formed under cool and wet climate and modified a rather different previous landscape characterised by erosion due to arid conditions during the Neolithic–Chalcolithic (Pre-LwU). The paleosol that culminates the long slope stability period reaches Ibero-Roman times. This implies that the paleoenvironmental conditions of the central sector of the Ebro Depression allowed the development of soils until that period. Afterwards, an accelerated degradation of soils began as a result of the intensification of the anthropic activities, especially from the late Roman period. The UpU is the second great moment of slope aggradation and had at least two stabilisation periods that allowed the development of two poorly developed soils. This stage is related with the cool periods of the LIA, whose effects are scarcely known in the lower areas of the Mediterranean region.

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