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Holocene environmental variability in the Central Ebro Basin (NE Spain) from geoarchaeological and pedological records

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ABSTRACT

Environmental fluctuations during the Holocene caused important landscape changes in the Central Ebro Basin, which is a very sensitive region due to its semiarid climate, lithology, and continuous human presence. Severe erosion processes hinder palaeoenvironmental and archaeological record preservation. Infills of ephemeral stream valleys in semiarid environments are some of the best contexts for geoarchaeological studies. In this paper, we analyse the geomorphological processes, pedological features, and charcoal and pollen content and composition of the sedimentary sequence of La Poza Valley catchment area, with the support of additional information from La Bajada Valley. ^{14}C dates for 13 charcoal fragments provide the necessary chronological control. We describe 5 sedimentary units and a polycyclic sequence of six soils that covers most of the Holocene, beginning ca. 9.5 ky cal BP. Buried soils help to identify stability periods in the sedimentary sequence, while incision stages are detected through erosive contacts and terraced organisation of the sedimentary units. Charcoal and pollen content and composition, as well as the soil development, reveal an open forest of junipers and pines for the Early Holocene in the lower part of the sequence (mainly in Unit 1), very different from the current deforested landscape, also represented in the sequence (Unit 4). Thus, La Poza record shows the environment was favourable for hunter-gatherers from the Late Mesolithic and for the first Neolithic farmers. From then on, progressive degradation due to a combination of climate changes and increasing human pressure led to the current deforested landscape.

1. Introduction

The study of sequences of geomorphological processes in geoarchaeological contexts provides essential information regarding the genetic factors of these archives and the bidirectional relationship between climate and past human influences in the landscape during the Holocene (Bellin et al., 2013; Constante et al., 2011; Faust et al., 2004; Fuchs, 2007; Peña-Monné and Sampietro-Vattuone, 2014). In addition, buried soils and polycyclic soils within sedimentary sequences indicate periods of relative geomorphological stability and edaphic development, which are a consequence of favourable environmental conditions (Badía-Villas et al., 2013b; Zielhofer et al., 2009). Therefore, these combined records are an important source of information for the study of environmental variability and the impact of human activities (Ackermann et al., 2014).

Geomorphological studies of Holocene alluvial contexts have increased in number in the last 50 years because they offer the opportunity to evaluate the effect of climatic oscillations and human activities in the landscape. Vita-Finzi (1969) formulated the first model, which assumed the existence of two climate-driven aggradation phases in the Mediterranean region but a number of later case studies demonstrated greater variability in the rhythms and chronologies of the aggradation phases in alluvial Mediterranean infillings (Burillo Mozota et al., 1985; van Zuidam, 1976; Wagstaff, 1981). Later research has focused on short-term effects of abrupt climate changes and human activities. Thus, some studies highlight human-induced environmental change

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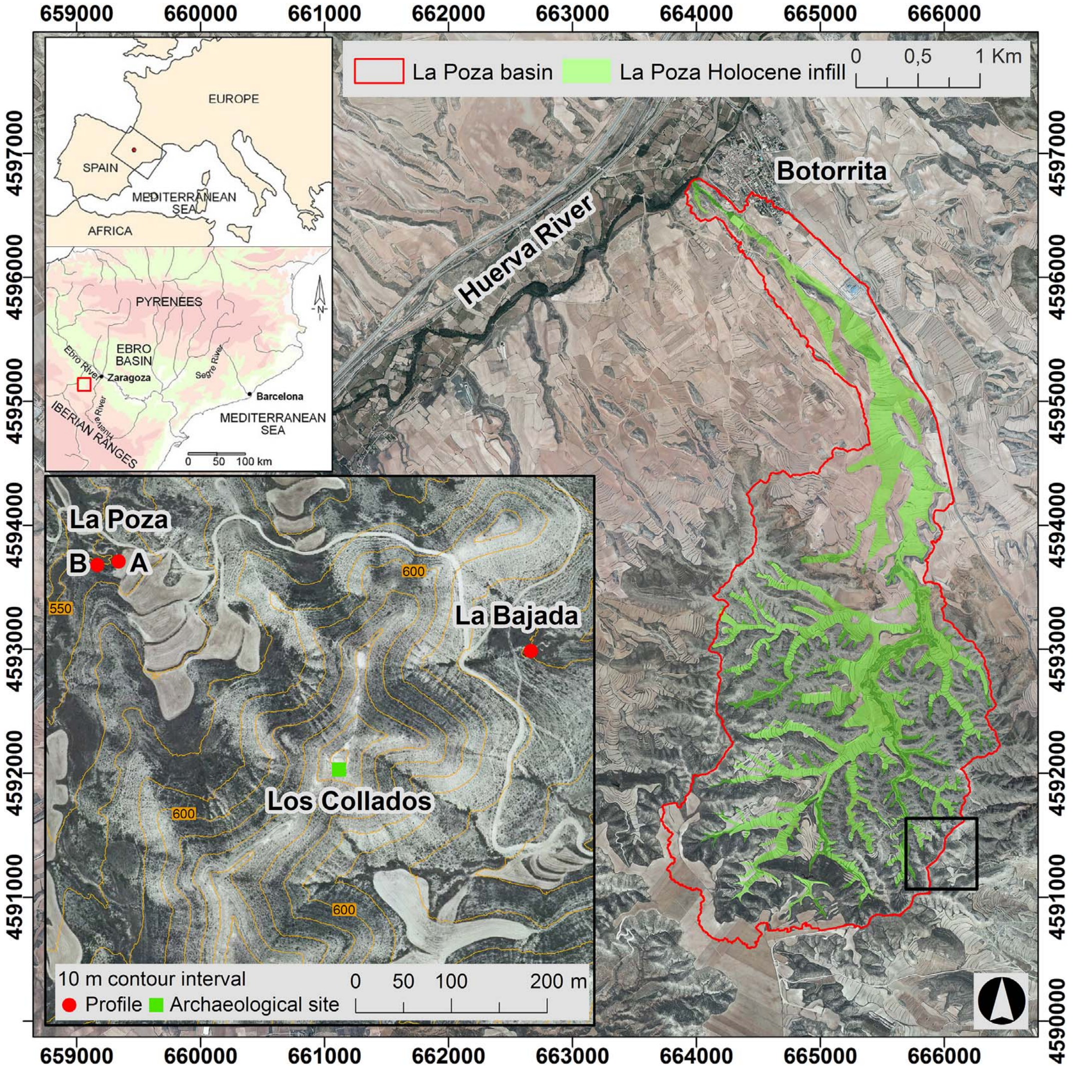

Fig. 1. Location of the study area with position of the studied profiles and the archaeological site of Los Collados. Limits of La Poza basin (red) and its Holocene infill (green) are also indicated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and how it was involved in the formation of new fluvial terraces and alluvial fans (Brückner, 1986; Butzer, 2005; Casana, 2008; Faust et al., 2004; Fuchs, 2007; Larue, 2002; Pope and van Andel, 1984; van Andel et al., 1990; Wagstaff, 1981; Zielhofer et al., 2008).

Conversely, other authors compare particular study cases with general models to identify the common processes and the local variations, and, finally reach complex explanations integrating climatic (general) and cultural (regional) factors (Bintliff, 2002; Constante et al., 2010, 2011; Peña-Monné et al., 2014; Pope et al., 2003; Schulte, 2003).

A number of studies emphasize the importance of palaeosols as proxy for climate change impact evaluation during the Quaternary (Badía-Villas et al., 2013b, 2015) and especially for the Holocene (Kühn and Pietsch, 2013; Pietsch et al., 2010; Pietsch and Mabit, 2012; Pietsch and Kühn, 2014; Retallack, 2001). In addition, linking these palaeosols with the regional chrono-cultural sequences, by means of absolute dating and the artefacts contained in the soils, provides insight into the difficult question about the bidirectional relation between environmental and cultural changes, especially regarding agricultural practices and deforestation processes (Bork, 1989; Dreibrodt et al., 2009; Harrower et al., 2010; Henkner et al., 2017; Kühn et al., 2010; Pietsch and Mabit, 2012).

The studies of valley infillings of ephemeral streams in the Central Ebro Basin (CEB, from here on) began four decades ago with van Zuidam's (1975, 1976) geomorphologic work, followed soon by Burillo Mozota et al. (1985) and Soriano (1989). From the beginning, the palaeoenvironmental interest of the valley infills was clear (Gutiérrez-Elorza and Arauzo García, 1994; Gutiérrez-Elorza and Peña-Monné, 1998; Peña-Monné et al., 1996), especially in an area where the climate and lithology (*cfr. Infra*: 1.1 regional settings) hinder the preservation of usual biological proxies, such as pollen (González-Sampériz et al., 2008). The most recent studies in the region have enhanced the chronological resolution of the infilling processes with broad radiometric dating sets and geoarchaeological control (Constante et al., 2009, 2010, 2011; Peña-Monné et al., 2004). Ephemeral streams in the CEB have three main Holocene accumulation levels separated by incision hiatuses, formerly named, from oldest to youngest, N3 to N1 (Gutiérrez-Elorza and Peña-Monné, 1998; Peña-Monné et al., 2004), but recently renamed H1 to H3, in chronological order (Peña-Monné et al., 2018). In this paper, we use this last nomenclature for Holocene accumulation levels.

This paper aims to interpret landscape evolution during the Holocene by means of geoarchaeological and pedological records. It focuses on the sedimentary sequence of the infill in the catchment area of La Poza Valley, eastern ephemeral tributary of the Huerva River that flows into the River Ebro, one of the main rivers in the Iberian Peninsula. Additionally, we provide complementary information regarding a nearby valley (La Bajada), whose catchment area shares a watershed with La Poza Valley.

Several reasons explain the importance of La Poza and La Bajada case studies in this research context. Increasing the set of studies in this region broadens our understanding of palaeoenvironmental dynamics in the Ebro Basin, and by extension in the Western Mediterranean Basin where long-term desertification is currently an important issue. Most previously studied Holocene palaeoenvironmental records in this region focus on the time from the Bronze Age to the Roman period (ca. 3.5 ky cal BP to 1.6 ky cal BP), while La Poza and La Bajada provide information regarding both older and younger phases of the Holocene. In addition, La Poza Valley is one of the main tributaries in the lower course of the Huerva River, similar and comparable to others that have already been subjected to study, such as La Morera and Las Lenas (Andres et al., 2002; Peña-Monné et al., 2004). And finally, the sedimentary infilling in La Poza preserves a buried sequence of polycyclic soils that has been subjected to an interdisciplinary study addressed from the combined perspective of geomorphology and pedology, with contributions from palynology and anthracology to depict the composition and status of the vegetation cover in the different phases recognized in the sedimentary and soil sequences.

In addition, a number of archaeological sites dated from the Mesolithic to the present day surround La Poza Valley (Bea Martínez et al., 2010; Pérez-Lambán et al., 2010; Rodanés Vicente and Picazo Millán, 2013). Understanding palaeoenvironmental evolution in the area is essential for the interpretation of this archaeological record and, at the same time, archaeological knowledge can provide information about the human-climate triggers of landscape evolution.

1.1. Regional setting

The area of this study is in the CEB; a Miocene continental sedimentary valley from a tectonic graben formed during the uplifting of the Pyrenean and Iberian mountain ranges. La Poza and La Bajada valleys are in the basin of one of the main tributaries of the River Ebro, the Huerva, which has its catchment in the Iberian Range and flows into the Ebro in the city of Zaragoza (Fig. 1).

In the central and southern sector of the CEB, the main rocks, from bottom to top, are clay and sandstones, gypsum and marls, and finally marls and limestones (Quirantes, 1978; Riba et al., 1983). These geologic materials maintain their horizontal position with very little and minor deformation. The opening of this basin to the Mediterranean Sea, at the end of the Pliocene (Urgeles et al., 2011), led to the incision of the drainage network by the Ebro and its wide network of tributaries in the Pliocene and Quaternary. In the interfluves, there are structural platforms or mesas (locally known as *muelas* or *planas*), whose uppermost layer is formed by resistant lacustrine limestones. These mesas form the highest relief in the area, reaching 700 m asl.

The present climate is Mediterranean-Continental with semiarid features. Mean annual precipitation is about 400 mm, unevenly distributed along the hydrologic year, and with a mean annual potential evapotranspiration above 1200 mm (Cuadrat et al., 2007). Therefore, aridity is a defining characteristic of the CEB, which is probably one of the driest inland regions in Europe. Its severe water deficit (ca. 1000 mm/yr) is caused by the rain shadow exerted by the surrounding mountains and is enhanced by the subsiding and drying NW-SE wind, locally known as *cierzo* (Cuadrat Prats, 2004).

Vegetation in CEB is an open halophyte steppe dominated by thermophilous species like *Quercus coccifera*, *Rosmarinus officinalis*, *Lygeum spartum*, *Artemisia herba-alba*, *Salsola vermiculata*, *Asphodelus cerasiferus*, *Brachypodium retusum* and *Limonium* sp., among others. The tree component is limited by small stands of *Pinus halepensis*, *Juniperus thurifera* and *Quercus ilex rotundifolia*. The flat areas and valley bottoms are occupied by rainfed cereal fields, vineyards, olive trees, and almond trees.

2. Materials and methods

This study describes the sedimentary sequences in the catchment of two ephemeral streams as they are visible in three profiles: La Poza A, La Poza B and La Bajada. The main profile, La Poza A, is 6 m thick and shows significant layering corresponding to potential buried soils as a result of the combination of geomorphological and edaphological processes. The other two profiles provide complementary information that confirms and fills the gaps in La Poza A.

The research strategy for this study was designed to integrate data from a set of different disciplines with their own methods. The spatial dimension of the resulting datasets has been represented and managed within a GIS, namely ESRI's ArcGIS software.

Detailed geomorphologic mapping of La Poza Valley was necessary to get a general view of the area and the current geomorphological processes and morphologies. The geomorphologic map was drawn, following the method and conventions proposed by Peña-Monné (1997), in ESRI's ArcMAP using aerial orthophotographs, stereoscopic photographs and a 1m-cell DEM derived from LiDar data (all data available from the Spanish National Geographic Institute: IGN www.ign.es). In parallel to drawing the map, the entire valley was surveyed to describe the geomorphological units and to identify good sampling sites. In addition, more extensive surveying was carried out to locate archaeological contexts that could be related to the valley infill.

Field description of soil horizons and sedimentary layers was done according to the FAO (2006) procedures, including colour (under moist and dry conditions), structure, consistency, and composition of each pedon. Soil samples collected from every horizon and layer were air-dried at room temperature and sieved into gravel (> 2 mm) and fine earth (< 2 mm) fractions. The standard method to obtain samples oven-dried to 105° C for further analyses was not followed in this work because the crystallization water of gypsum ($CaSO_4·2H_2O$) would have been lost; in order to compare properties of gypseous and non-gypseous soils, all soil samples were dried to 50° C until constant weight.

Fine earth (< 2 mm) fraction was used to measure physical and chemical soil properties. pH (1:2.5 ratio in H_2O) was determined using a glass electrode (McLean, 1982). Total carbonate content was measured volumetrically (with a calcimeter) after treatment with hydrochloric acid (Nelson, 1982). The electrical conductivity (ECe) and soluble K and Na content were measured in the saturated paste extract (Rhoades, 1982a, 1982b). Total soil organic C was determined by the wet oxidation method using the van Bemmelen factor (1.724) to estimate organic matter (Nelson and Sommers, 1982). Gypsum content of the soils was determined by a thermogravimetric method based on the loss of crystallization water of gypsum upon heating to 150 °C when gypsum is converted to anhydrite (Nelson et al., 1978; Vieillefon, 1979). The presence or absence of sulphates and chlorides were determined by reaction with $BaCl_2$ and $AgSO_4$ respectively.

In addition to soil and sediments, charcoal fragments and pollen samples were recovered for further analyses. Charcoal fragments for the anthracological study were recovered from ca. 3 kg sediment samples, one for each of the 18 sampling layers. Each sample was weighed, dissolved in water and passed through 4, 2 and 1 mm sieves to recover and classify the different fragments. Charcoal remains were air-dried and weighed in order to calculate the general anthracomass of each layer (AMG), that is, the proportion of charcoal in the sediment (w/w). Anthracological observation of the three anatomical planes of the wood (transversal, longitudinal-radial, and longitudinal-tangent) was performed according to standard procedures (Vernet et al., 1979). For botanical determination, plants, wood and charcoal anatomy atlases were used (García Esteban et al., 2003; Schoch et al., 2004; Schweingruber, 1990; Vernet et al., 2001) as well as the burnt wood reference collection available at the University of Zaragoza.

Pollen analyses were carried out in samples of 1 cm thickness in the sedimentary profile. Laboratory procedures followed the classic chemical method (Moore et al., 1991), modified according to Dupré (1992), and using Thoulet and *Lycopodium clavatum* tablets (Stockmarr, 1971). Pollen sum was always higher than 300 terrestrial grains per sample, and taxa number not < 20. Hygro-hydrophytes, ferns, and algal remains were excluded for percentage calculation. The pollen diagram has been drawn using Psimpoll (Bennett, 2009) and only includes selected taxa and the trees/shrubs/herbs component in order to decipher the main vegetation changes in the landscape.

The chronological control of sedimentation and evolution on the profile is based in thirteen ^{14}C dates of charcoal fragments of *Juniperus* sp. and *Pinus halepensis*. ^{14}C dates were determined by Gröningen University and DirectAMS laboratories and calibrated using OxCal 4.2 software and the IntCal13 calibration curve (Reimer et al., 2013). Archaeological artefacts were not found in the studied profiles, so no direct chrono-cultural information related to sedimentation process is available. However, there is context information from a nearby archaeological site called Los Collados (Pérez-Lambán, 2013; Pérez-Lambán et al., 2010). It is a Bronze Age settlement (4.1 to 3.8 ky cal BP) 300 m above the La Poza profile location, on a narrow mesa on the watershed of La Poza basin. This settlement was built in mud and timber, partially surrounded by a stone wall, and was destroyed ca. 3.8 ky ago by an intense fire leaving a large volume of fired mud, pottery and charcoal fragments.

3. Results

3.1. La Poza Valley

Regionally, most valleys in the area have flat bottoms (locally known as *vales* in plural, or *val* in singular) as a result of the Holocene infill accumulations produced by the erosion of surrounding slopes and maintained by levelling and terracing for cultivation.

La Poza Valley is a 7.3 km long ephemeral stream with a basin that covers 840 ha. It flows from a structural platform (650 m asl) to the Huerva River (360 m asl) (Fig. 2). Overall altitude difference is 290 m in a horizontal distance of 7.3 km. Therefore, the mean gradient of the gully is ca. 4%. However, La Poza has three clearly differentiated courses.

The upper course includes the first 3 km of the valley and a dense dendritic network of tributary ravines. Here the basin is widest, reaching 2.5 km wide. The difference in altitude in the upper course is 200 m, and the mean gradient is 6.7%. However, the slopes of the structural platform and the slopes on both sides of the gullies of the upper course network reach 60%. This high gradient is due to the Quaternary incision of the fluvial network in the highly-erodible Miocene materials in CEB. Deep recent incision in the Holocene infilling of the valley modified its former flat bottom morphology (Fig. 2). Inside this incision, further accumulations and incision sequences occurred. It is an upwards incision resulting from a combination of piping, basal undermining, and surface run-off. When pipes and basal hollows are large enough, they collapse generating an incision with vertical walls. At the same time, inside the incision, running water is channelled causing an intense lineal incision after heavy rains. In some areas, this incision in the Holocene infill is > 20 m deep and reaches the Miocene substratum. It is in this highly variable geomorphological context where the studied profiles are located: two of them in the catchment of La Poza stream (La Poza A and B profiles) and the other one in the catchment of a neighbouring stream (La Bajada profile).

The mid-course of La Poza stream flows through flatter terrain, between the structural platform and the alluvial plain of the Huerva River. In this sector, La Poza stream descends 50 m in 2.3 km, with a constant gradient of 2.17%. The basin of the middle course is narrower and straighter than the upper one, and its trajectory is parallel to other valleys and perpendicular to the main river. Therefore, there are no tributaries of La Poza in the middle or lower courses. Both sides of the valley consist of gentle low hills. Some of them have detrital materials on top, proving that they are residual hills of old pediments. The valley bottom in the middle course is flat and has no incision because the slopes of the course and the valley sides are not steep enough.

The lower course maintains the same general gradient as the middle one. The lower valley is bordered by the remains of pediment levels and high old terraces that have been dated to the Pleistocene in other parts of the Huerva Valley (Peña-Monné et al., 2004). The eastwards displacement of the Huerva River has completely eroded the alluvial fan of La Poza stream and it has enhanced the escarpment on the left side of the alluvial plain. This change in the base level of La Poza Valley led to an incision of the infill in the lower course. Despite the severe erosion and anthropogenic topographical transformations of this area due to the proximity of the town of Botorrita, there are at least two accumulative stages in the lower section of La Poza Valley.

3.1.1. La Poza A profile

3.1.1.1. General features. The main profile analysed in La Poza Valley catchment reaches 6 m in depth. It is located in the upper course of the valley, just in the foot slopes of the small mesa of Los Collados (Fig. 3). The profile stands in the wall of a deeply-incised circus-shaped headcut, with vertical lateral downstream walls.

The natural profile was manually deepened to complete the sedimentary sequence by reaching the Miocene gypsum bedrock. The resulting profile shows granular and colour variations, indicating the presence of different sedimentary units and pedogenic horizons. Eighteen layers were numbered from top to bottom (E1-E18) and used as sampling units and as positioning references through the profile. The sequence was also divided into 4 sedimentary units (Fig. 4) according to their texture, pedofeatures and the arrangement of their components (differences in colour are due to pedogenic processes and the presence of charcoal fragments).

Channel structures of coarse material are evident in Units 2 to 4, but not in the basal one. Angular gravels and pebbles mainly consist of limestone and marlaceous limestone fragments from the upper strata of the Miocene sedimentary sequence. The origin of these rocks is the higher part of the catchment of the gully, ca. 150 m away from the profile. Their presence in the profile is due to longitudinal transport processes. Gypsum rock fragments are in the minority, and virtually restricted to the base of Unit 1 (E18) in contact with the gypsum bedrock, to the bigger channels in Unit 2 (E10), to the base of Unit 3 (E8–E9), and to the uppermost part of Unit 4 (E1). Fine material from all units mainly consists of silt resulting from weathering of local gypsum and marls.

La Poza A profile provided ^{14}C dates from 9.5 to 0.4 ky cal BP (Table 1). It belongs to the first two Holocene infill levels (H1 and H2) according to the morpho-sedimentary sequence for CEB (Peña-Monné et al., 2018).

These sedimentary units contain a polycyclic soil sequence (Fig. 5) consisting of five buried soils beneath the current functional soil. The morphological characteristics of each unit and soil classification (IUSS Working Group WRB, 2015) and specific morphological and physical-chemical properties of each soil horizon are given below. Extended and detailed data on each horizon can be found in Table 2. Additional information regarding the vegetation cover derived from charcoal and pollen analysis is also provided (Figs. 6 and 7).

Both charcoal fragment and pollen content clearly reveal the existence of two botanical contexts in the profile. The first one coincides with Unit 1, which is very rich in charcoal (723 mg/kg in E13) and where the vegetation taxa recorded differ from the current landscape. The second one reflects the current vegetation cover and basically corresponds to Unit 4, except for the last two horizons. Overall, 819 charcoal fragments with sizes between 2 and 8 mm have been recovered in 11 horizons in the profile. E1, E2, E5, E10, and E18 are sterile; E6 and E17 contain insignificant amounts (< 5 mg/kg) of charcoal fragments under the minimum size for determination. Taxonomic determination was possible in 69.7% of the sample. The level of indeterminacy is explained by the small size and by the high frequency of vitrification of many charcoal fragments. The 571 determinable charcoal fragments were classified in 11 taxa. Three of them belong to conifers (*Juniperus* sp., *Pinus halepensis*, *Pinus* sp. cf. *halepensis*)

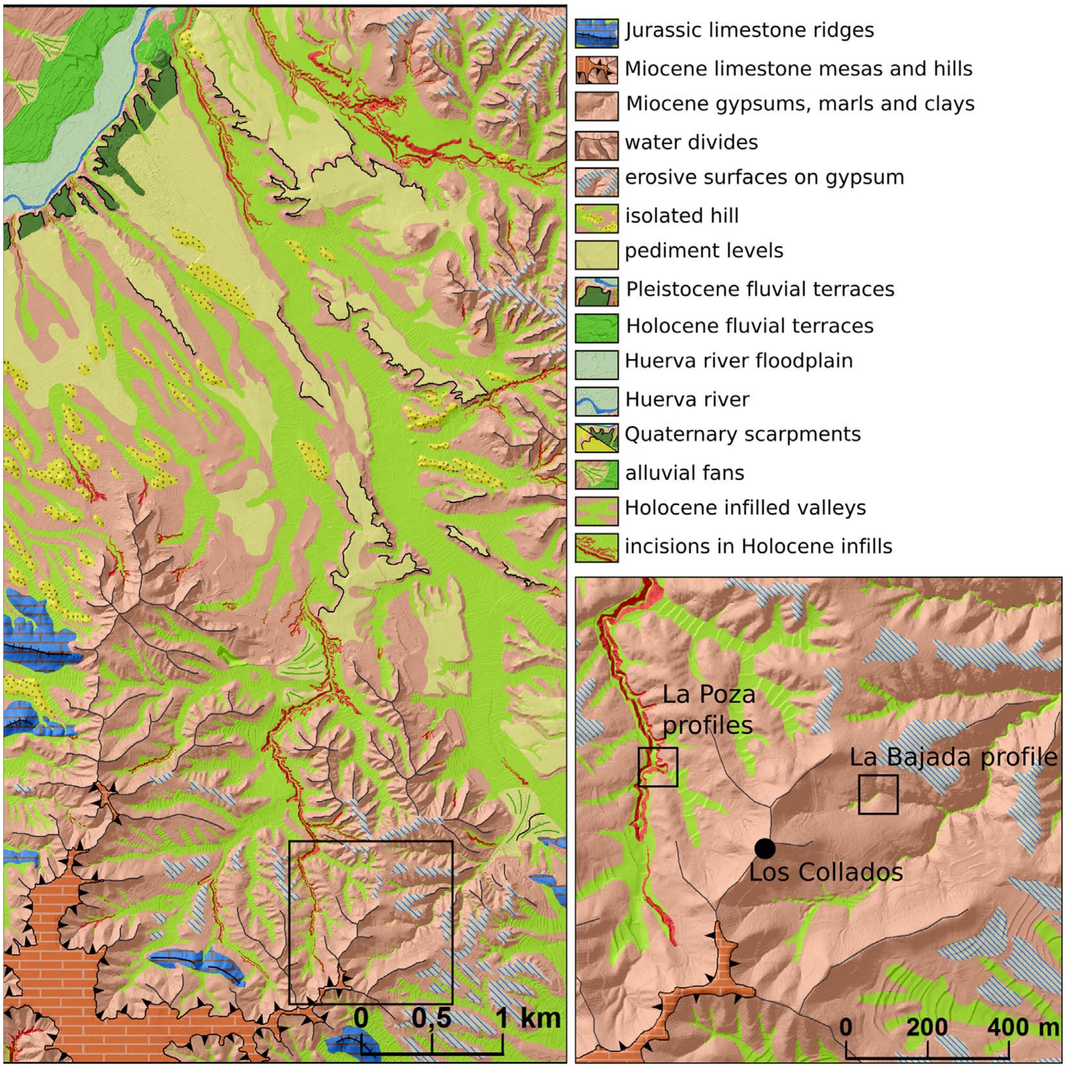

Fig. 2. Geomorphological map of La Poza and Las Vales valleys, with the position of the studied profiles in La Poza and La Bajada catchment areas.

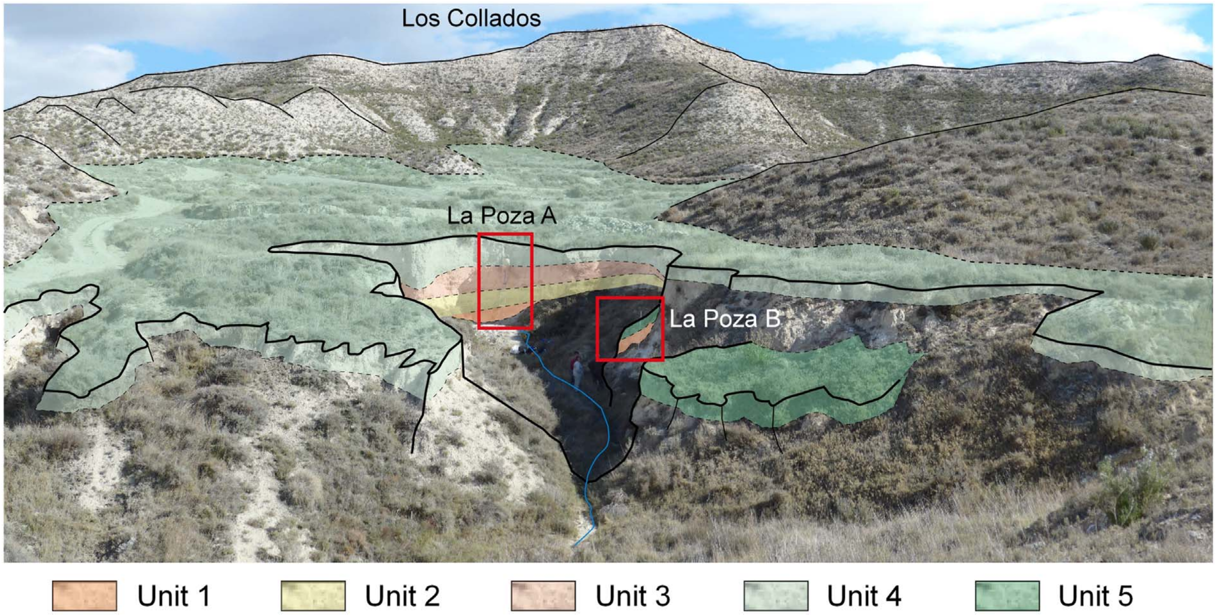

Fig. 3. General view of La Poza catchment and gully-headcut, with the location of La Poza A and La Poza B profiles.

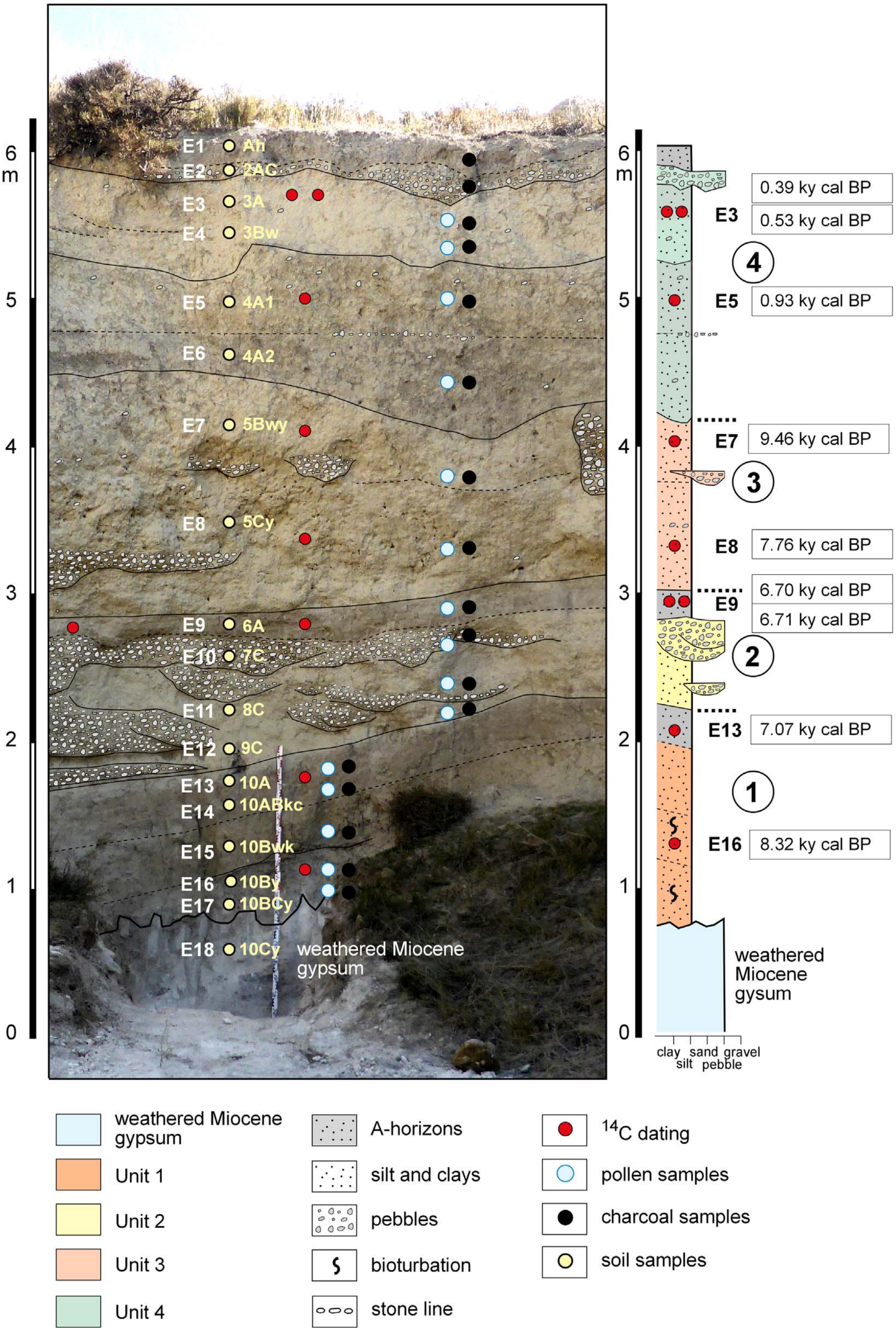

Fig. 4. Chrono-stratigraphic profile of La Poza A, with indication of units and layers. Also soil, pollen, charcoal, and ^{14}C samples are indicated.

and the other eight to angiosperms, both monocotyledoneae and dicotyledoneae (Fabaceae, *Quercus ilex/coccifera*, *Rosmarinus officinalis*, *Rhamnus/Phillyrea*, Rosaceae/Maloideae, *Prunus* sp., cf. *Cistus* sp.).

Regarding palynological results, the middle part of the profile (E7 to E12) was sterile, but analyses were statistically significant in the upper (E3 to E6) and basal (E13 to E17) sectors. Overall, 82 different taxa (both pollen and spores, and non-pollen palynomorphs or NPPs) have been identified.

3.1.1.2. Unit 1. Unit 1 is the basal part of the profile, in contact with the geological substratum, composed of alabastrine gypsum and gypseous marls. It comprises layers E13 to E18. Fluvial morphologies

Table 1
^{14}C dates from La Poza and La Bajada profiles.

Profile	Lab. code	Geom. unit	Layer	^{14}C yr BP		Cal yr BP (95.4%)				
				BP	1σ error	From	To	Mean	Median	1σ error
La Poza A	D-AMS 011140	4	E3	297	22	436	298	376	391	44
	D-AMS 013261		E3	509	27	620	505	532	528	21
	D-AMS 013262		E5	1003	26	965	801	917	928	40
	D-AMS 15979	3	E7	8482	69	9556	9309	9479	9490	56
	D-AMS 15980		E8	6923	74	7931	7621	7767	7762	76
	D-AMS 011141	2	E9	5876	28	6774	6640	6700	6700	31
	GrA-47553		E9	5885	45	6844	6567	6708	6708	53
	D-AMS 011142	1	E13	6174	28	7166	6992	7079	7079	51
	D-AMS 15981		E16	7500	65	8407	8188	8304	8315	65
La Poza B	D-AMS 013263	1	–	7200	35	8155	7951	8014	8005	44
	D-AMS 011143		–	7379	28	8320	8062	8217	8203	57
La Bajada	GrA-47552		–	620	35	660	547	604	601	33
	D-AMS 015708		–	936	22	929	766	852	854	37

^{14}C ages were calibrated to 'calendar' ages by using OxCal 4.2 based on Reimer et al. (2013) calibration data set.

are absent in Unit 1 and its gradient is relatively high. From a geomorphological perspective, it is a slope deposit. The sediments in Unit 1 are mainly silt-clay material, rich in edaphic gypsum and calcite that come from the weathering of the substratum. Translocation of dissolved gypsum is shown by the increase in gypsum content with depth, from 8 to 12 and finally to 68% (16% in E13 is interpreted as a translocation of edaphic gypsum after the sedimentation of Unit 2). Secondary calcite (nodules and pseudomycelia) is present in the upper part of the profile, and calcium carbonate translocation occurred in the profile, with an increase from 25% to 33% with depth, but a significant

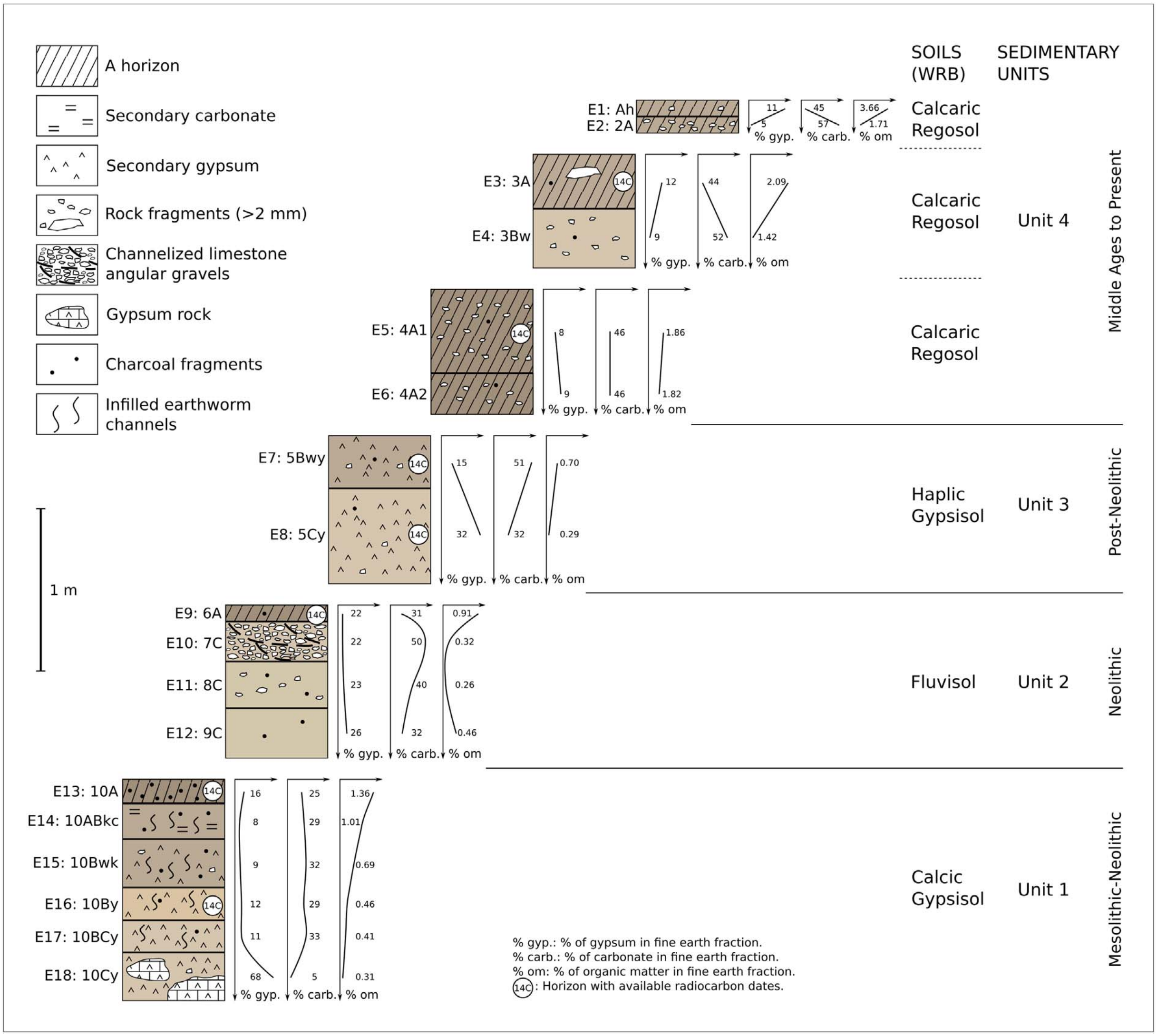

Fig. 5. Polycyclic soil sequence in La Poza A profile.

Table 2
Main physical and chemical properties analysed in the polycyclic soil sequence in La Poza A profile.

Geom. unit	Layer	Depth (cm)	Genetic soil horizon	Texture	Stones (%)	Munsell colour notation (wet; dry)	Soil moisture content (% air-dried; % saturated)	$CaCO_3$ eq. (%)	Gypsum (%)	Organic matter (%)	pH (1:2.5)	ECe 25 °C (dS/m)	Soluble K (mg/l)	Soluble Na (mg/l)
Unit 4	E1	20	Ah	Sandy loam	4.9	10YR 7/2 10YR 4/2	1.9 60.3	45.0	10.7	3.7	7.9	2.6	63.0	19.6
	E2	40	2A	Sandy loam	26.3	10YR 7/2 10YR 4/2	1.88 60.19	57.0	4.8	1.7	7.9	2.8	67.3	38.3
	E3	73	3A	Loam	9.4	10YR 7/1.5 10YR 4/1.5	2.0 60.3	44.5	12.4	2.1	8.0	4.0	28.1	68.6
	E4	109	3Bw	Clay loam	11.4	10YR 7.5/2 10YR 5/2	1.8 51.8	51.9	8.9	1.4	8.1	11.9	8.2	358.6
	E5	160	4A1	Sandy clay	14.8	10YR 6.5/1 10YR 4.5/2	2.1 49.9	45.7	8.2	1.9	7.9	13.3	8.3	386.4
	E6	185	4A2	Sandy clay	11.9	10YR 6.5/1 10YR 4.5/2	2.0 49.7	46.2	9.4	1.8	7.9	8.8	6.6	208.7
Unit 3	E7	217	5Bwy	Sandy loam	4.8	10YR 7/2 10YR 5/2	1.4 46.4	50.7	15.3	0.7	7.9	5.9	9.8	120.1
	E8	275	5Cy	Sandy loam	2.5	10YR 8/2 2.5YR 6/3	1.1 49.4	31.9	38.4	0.3	8.0	3.8	11.0	52.3
Unit 2	E9	285	6A	Silty clay	0.0	10YR 6/2 10YR 3.5/2	1.7 52.4	31.3	22.2	1.6	7.9	5.3	5.2	70.5
	E10	309	7C	Sandy loam	84	10YR 8/2 10YR 6/2	1.2 48.7	50.2	22.4	0.6	8.0	7.6	19.4	220.9
	E11	337	8C	Sandy clay	10.2	2.5YR 8/1 2.5YR 5.5/2	1.3 44.0	40.3	23.1	0.4	8.1	5.4	8.3	181.1
	E12	367	9C	Clay loam	0.0	2.5YR 8/1 2.5YR 5.5/2	1.3 45.6	31.9	25.8	0.8	8.1	5.6	11.2	181.1
Unit 1	E13	382	10A	Clay	0.0	10YR 6/2 10YR 3/2	1.8 58.2	25.5	16.3	1.4	8.3	7.9	4.7	410.7
	E14	403	10ABkc	Silty clay	0.1	10YR 6.5/2 10YR 4/2	2.0 57.3	28.8	8.1	1.0	8.3	8.3	3.3	401.5
	E15	432	10Bwk	Clay	4.1	10YR 7/2 10YR 5/3	2.0 56.1	32.4	8.6	0.7	8.2	9.0	3.5	299.0
	E16	452	10By	Silty clay	0.0	10YR 7.5/2 10YR 5.5/2	2.3 56.3	29.4	11.5	0.5	8.2	11.5	4.3	420.0
	E17	471	10BCy	Loam	0.0	10YR 7.5/1 10YR 6/2	1.9 54.8	32.7	11.4	0.4	8.1	6.2	2.1	190.5
	E18	500	10Cy	Sandy loam	0.6	10YR 8/1 10YR 7/2	0.7 41.1	5.3	68.1	0.3	8.2	4.5	5.8	155.6

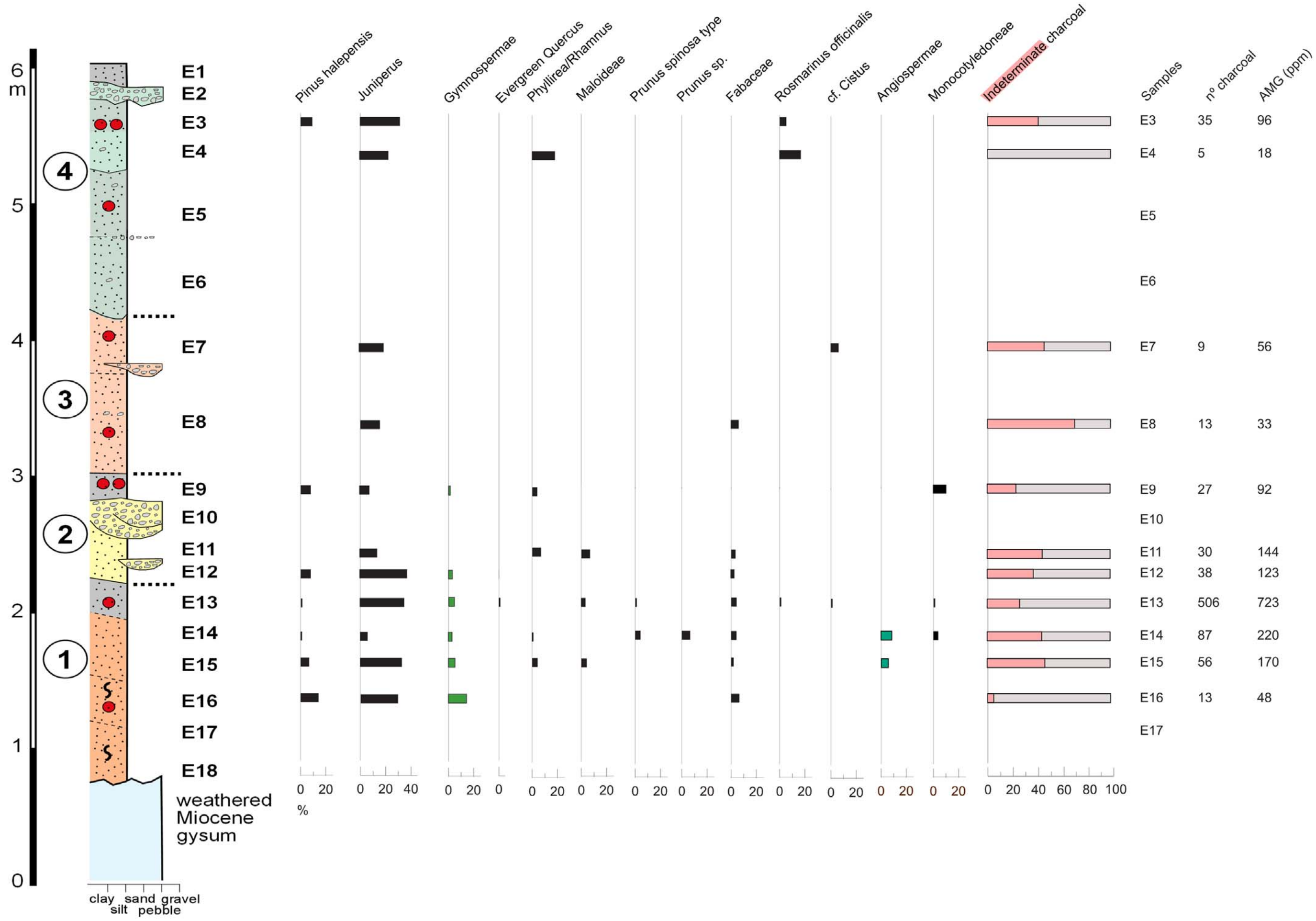

Fig. 6. Anthracological plot of La Poza A profile.

decrease in the basal part. This distribution of calcium carbonate and gypsum is explained by the higher solubility of the latter. In addition, Unit 1 also received colluvium material evidenced by scarce limestone gravels. Altogether, the evidence makes Unit 1 a slope deposit at the base of a hillslope formed by pedogenic processes with some colluvium contributions.

The soil in Unit 1 responsible for the origin of this deposit is the best-developed soil in the studied profile with its *sequum* A-ABkc-Bwk-By-BCy-Cy-R (E13 to E18; R = Gypsum rock), and has been classified as a Calcic Gypsisol (Fig. 5). The translocation of edaphic or secondary gypsum (y) and calcite (k), as already mentioned, is an important feature within this profile. The A-horizon (15 cm thick) is darker than the underlying horizons. Organic matter content is relatively high in A and decreases significantly with depth. The organic matter content pattern of the soil is typical of this kind of soil (Badía-Villas et al., 2013a) and similar to those developed in well-drained forest soils (Brady, 1984). Subangular blocky structure is very well developed from ABkc to BCy horizons; it is only partially lost on the surface due to compaction and the large amount of charcoal fragments. The soil structure and the abundance of translocation and bioturbation features preserved in this palaeo Calcic Gypsisol in Unit 1 are signs of a well-developed, fertile soil, probably formed under a forestry environment. Its thickness guarantees a very high water-holding capacity, which favoured the open tree cover of junipers and pines.

Unit 1 is the richest in charcoal content. General anthracomass in its superficial horizon reaches 723 mg/kg and remains high in the others, although there is a decrease with depth. Presence of charcoal fragments in subsuperficial horizons can be explained by vertical movements through faunal galleries and desiccation cracks in clayey material, and by lateral displacement with the colluvium inputs. A fire in a relatively dense vegetation cover, which provided a large mass of wood fuel, produced this large number of charcoal fragments. Charcoal composition in Unit 1 is very heterogeneous; the vegetation was dominated by junipers (*Juniperus* sp.) and, to a lesser extent, by *Pinus halepensis*, Fabaceae and Rosaceae/Maloideae, which are also well represented. Although only occasionally represented, evergreen *Quercus* charcoal is also found in this unit (Fig. 6).

Pollen content in Unit 1 reveals the maximum frequencies of trees (Fig. 7). Junipers are locally present, but most of the pollen comes from pines. *Pinus halepensis/pinaster* type attains its highest frequencies in this unit, despite *Pinus nigra/sylvestris* type being dominant. In contrast, *Quercus ilex/coccifera* and *Quercus pyrenaica/faginea* types, as well as *Corylus*, are practically absent. Shrubs like Rosaceae and Lamiaceae are also vegetation components, like Poaceae, Chenopodiaceae, Compositae (mainly Cichorioideae, Asteroideae, *Carduus*) and Fabaceae in the herbaceous layer (Fig. 7).

Apparent discrepancy between charcoal fragments and pollen content in the contrasting frequencies of junipers and pines can be explained by the different geographic catchment areas of both proxies (anthracology is a local vegetation proxy whereas palynology is more regional). Charcoal fragments come necessarily from the area surrounding La Poza (Fig. 6), which was probably covered by an open vegetation community which included junipers and, perhaps, isolated pines, whereas the regional vegetation would be formed by pinewoods. Therefore, junipers provided most of the charred wood at La Poza site while pines, probably further away, contributed a larger amount of

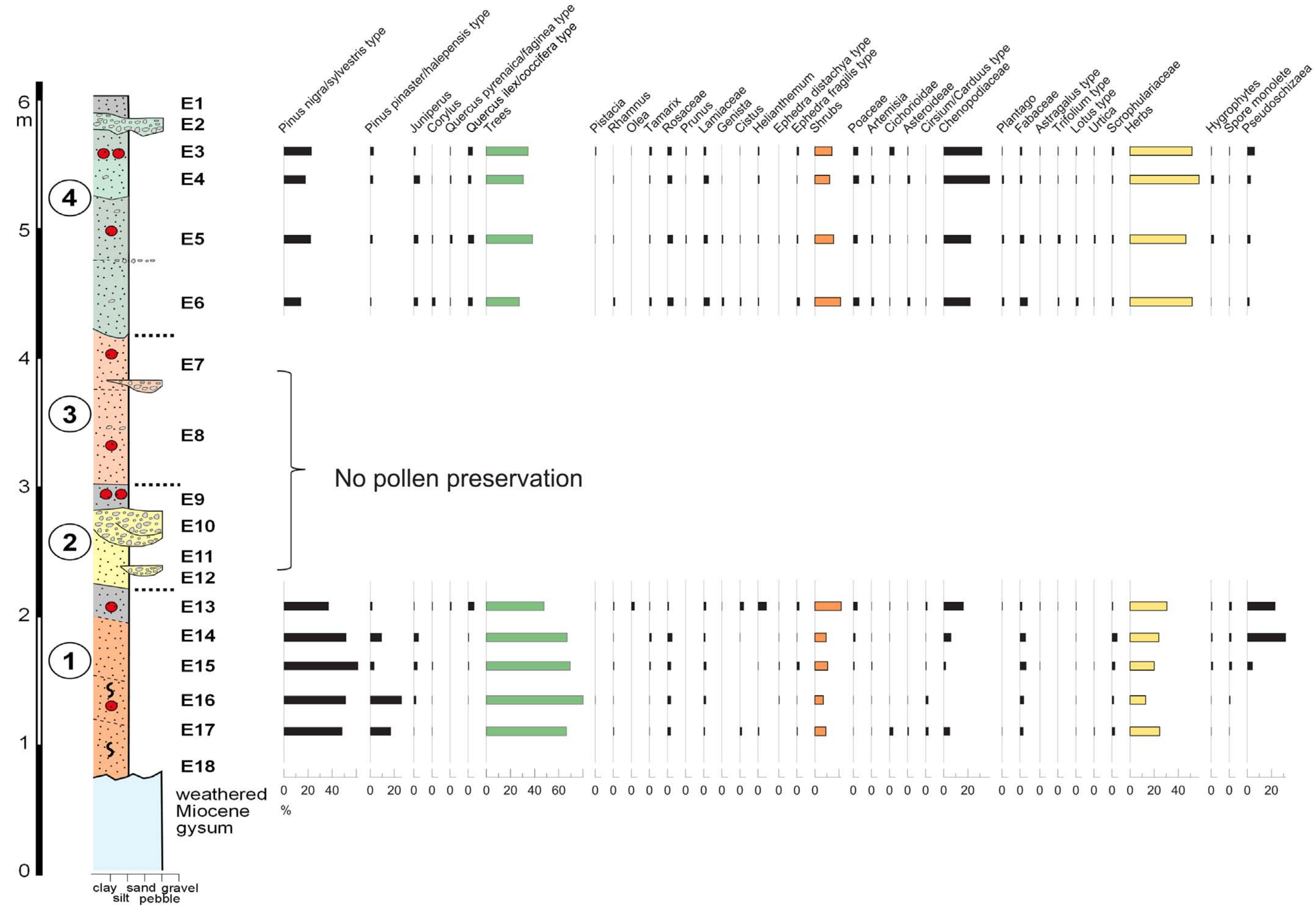

Fig. 7. Palynological plot of La Poza A profile.

pollen due to their high productivity and long-distance dispersion.

This slope deposit and well-developed Gypsisol provided two ^{14}C dates from the Early-Middle Holocene, comprising the Mesolithic cultural period. The first one from E16 goes back to 8.3 ky cal BP, while the surface one from E13 is 7 ky cal BP (Table 1). This gives a minimum time span of 1.3 ky for this deposit and soil development. However, as will be argued in the Discussion section, its development probably began ca. 9.5 ky ago, so the time period represented by Unit 1 expands to 2.5 ky.

3.1.1.3. Unit 2. Unit 2 (E10-E12 layers) lies on top of the slope deposit (Fig. 4). Its alluvial origin is clear as it comprises channels of gravel within more loamy-sandy material. At some extent, there is cross stratification of channels in this unit, whose origin is clearly related to hydric processes with longitudinal short-distance transportation of coarse material (especially in E10). In comparison with the previous sedimentary phase (Unit 1), this unit represents an increase in fluvial activity resulting from more intense rain combined with less plant cover protecting the soil. The abundance of limestone gravel indicates transport from the overhanging escarpments of the limestone mesas.

Sediment layers in Unit 2 have a heterogeneous texture, high stone content and no edaphization signals. Therefore, they display no structure nor symptoms of translocation of solutes. Only the uppermost layer (E9) shows signs of incipient pedogenesis. It is a thin horizon (10 cm thick) which, in comparison with the underlying sediments (E10–E12), has finer texture, some degree of structuration, solute translocation, higher organic matter content, and abundant ash and some charcoal fragments. This layer must have been an exposed surface for the minimum time needed to accumulate these fire remains. It is interpreted as the A-horizon from a Fluvisol with *sequum* 6A-7C-8C-9C (E9–E12), which is the least-developed soil in the profile sequence (Fig. 5).

Charcoal content in the basal horizons of Unit 2 (E11 and E12) is high (> 120 mg/kg), probably due to transport of materials from the surface of Unit 1; the charcoal composition is almost identical. Above them, the largest pebble (fine to very coarse gravel) channel is a hiatus with no charcoal fragments (E10), while the surface horizon of Unit 2 (E9) is again rich in charcoal fragments (92 mg/kg) of *Pinus halepensis* and junipers (Fig. 6). Palynological samples in this unit show no pollen preservation (Fig. 7). Two ^{14}C dates from E9 place this Fluvisol in 6.7 ky cal BP (Table 1), that is, during the expansion of the Neolithic in the region.

3.1.1.4. Unit 3. Layer E9 is a tipping point in the sedimentary sequence. Unit 3 (Layers E7–E8) is formed by finer materials than Unit 2, and the gravel channels are less frequent and thinner. Sedimentation in this unit is a combination of lateral inputs of fine material coming from the slopes and longitudinal transportation of gravels or fine material in flows of varying energy. The rippled contact existing between Units 3 and 4 points to an erosive stage. If that is the case, we can assume a loss of sediments from the upper part of Unit 3.

Sediment in E7 has a moderate subangular blocky structure with frequent edaphic gypsum with pseudomicelia morphology (Bwy). Under it, E8 is a layer of massive gypsum lacking structure that has been named Cy (Fig. 5). This makes an incomplete soil *sequum* from a Gypsisol that lacks its A-horizon due to the erosion of the upper part of Unit 3. Leaching of gypsum from this absent A-horizon would be responsible for its accumulation in depth: 15% in Bwy and 38% in Cy.

Unit 3 contains charcoal of *Juniperus* sp., Fabaceae and *Cistus* (Fig. 6). It is noteworthy that charcoal remains from the latter two taxa are only present in E7 and in Unit 1. The two ^{14}C dates from this Unit 3 (from layers E7 and E8) (Table 1) return to the Early-Middle Holocene (9.5 and 7.7 ky cal BP). This chronological inversion and the charcoal composition are arguments to consider that the dated pieces of charcoal from E7 and E8 come from Unit 1.

3.1.1.5. Unit 4. There is a long stratigraphic hiatus between Units 3 and 4. Most likely it is due to a degradative period that eroded the upper part of Unit 3, which we have named Unit 3 + (see the Discussion section).

Unit 4 (E1–E6 layers) is somewhat similar to Unit 3, but with absence of fluvial channels. Unit 4 is divided into 3 subunits: 4a (E5–E6) is coarser and darker than Unit 3; 4b (E3–E4) is finer than 4a and it contains some cobbles (not present in other units of the profile); and 4c (E1–E2) is rich in pebbles and is severely affected by recent agriculture.

These subunits result from the superimposition of three soils formed by A-horizons or A-B *sequums* with some structure development and neither gypsum nor calcium carbonate translocation. All these soils are classified as Calcaric Regosols (Fig. 5).

The first subunit is formed by Layers E5 and E6. Their properties are almost identical, but a horizontal non-channelized thin layer of gravel, indicating a short hiatus in sedimentation, separates them. Besides this distinction, this subunit is rather thick (ca. 50 cm in E5 plus 25 cm in E6), and it has a relatively large amount of coarse material. Additionally, it has a slightly dark colour, coherent with its organic matter content, and a moderate granular structure. Thus, it was classified as a Regosol with *sequum* A1-A2 (E5 and E6). The superimposition of A-horizons and their thickness indicates cumulization, a combination of continued sedimentation with structuration processes and a herbaceous cover with deep radicular system that incorporated organic matter in a homogeneous distribution with depth (not as in forest soils). In fact, this is consistent with a trees-shrubs/herbaceous pollen ratio favourable to herbaceous taxa (Fig. 7). The only ^{14}C date from this soil places it in the Middle Ages, in the 11th Century AD (0.93 ky cal BP) (Table 1).

The second Calcaric Regosol is better developed than the previous one, forming a *sequum* A-Bw (E3–E4) (Fig. 5). It is noteworthy that charcoal fragments are abundant (ca. 100 mg/kg) in the A-horizon, while they are scarce in Bw (ca. 18 mg/kg). Beside junipers and pines, *Rosmarinus officinalis* and *Rhamnus/Phillyrea* charcoal reaches significant amounts, reflecting a vegetation composition similar to the current one (Fig. 6). Similarly, pollen is well-preserved in the surface horizon (E6) of this unit. Tree pollen content shows a marked decrease from Unit 1, synchronous to the expansion of the herbaceous component evidencing an open vegetation cover. *Pinus nigra/sylvestris* type continues to be the main representative taxa, although *Juniperus*, *Corylus* and both *Quercus* types are contributing to the pollen spectra. The marked decline of *Pinus pinaster/halepensis* type in this unit should be noted (Fig. 7). According to two ^{14}C dates from E3, this soil formed in the Late Middle Ages and Early Modern Age: 15th and 16th Centuries AD (0.53 and 0.39 ky cal BP) (Table 1).

Finally, the uppermost layers in the profile (E1-E2) were formed by a new sedimentary input and they are the current surface soil with *sequum* Ah-AC. Remarkably, charcoal fragments are absent from this last soil. The most superficial horizons have finer textures, as evidenced by their higher moisture content at saturation point.

3.1.2. La Poza B

Inside the incision where La Poza A profile is found, a nested terrace corresponds to the third Holocene infilling phase (H3). This is visible in La Poza B profile, 5 m downstream from La Poza A, in the topographical left side of the incision (Figs. 3 and 8).

The explanation of this nested terrace is complex. After the accumulation of Unit 4, an intense and lasting incision phase began. This incision in the valley infill generated a gully of vertical sides and circus-shaped headcut. This morphology results from headwards erosion by piping and basal undermining processes. The incision reached Unit 1 but stopped before reaching the bedrock. Later, a new accumulation (Unit 5) covered the remains of Unit 1.

The resulting profile (Fig. 8) has a basal layer of irregular thickness (30–100 cm) consisting of powdery white material produced by weathering of the underlying gypsum rocks. It also contains gypsum rock fragments with dissolution traces. The material in this basal layer resembles Layers E18 and E17 in La Poza A, Unit 1. Above it, there are the remains of an accumulation of darker material, with very irregular basal contact and 25–40 cm thick. It is massively bioturbated with worm galleries infilled with fine grey sediment. Two ^{14}C dates (8.2 and 8 ky cal BP) (Table 1) confirm its correspondence with E16 from La Poza A profile, Unit 1. Two pollen samples were analysed for comparison with La Poza A profile but both resulted sterile. Finally, a 40 to 60 cm thick layer of sediment sealed La Poza B profile (Unit 5). For an undetermined period, this last accumulation was the valley bottom corresponding to the H3 stage in the regional evolutionary model. No valid sample for ^{14}C dating was recovered from this Unit 5. However, it formed after the incision that eroded Unit 4, so it can be assured that Unit 5 is younger than 0.39 ky cal BP. Finally, erosion was reactivated and a new incision reached the bedrock, leaving La Poza B profile isolated.

3.2. La Bajada profile

This profile belongs to a neighbouring ephemeral stream called La Bajada (Figs. 1 and 2) that has its catchment area east of Los Collados mesa, that is, on the opposite side to La Poza stream. It flows over 2.1 km, from Los Collados mesa into the Barranco de las Vales, another ephemeral stream tributary of Huerva River. In this short course, it descends 190 m, resulting in a general gradient of 9%. Consequently, its valley is deeply incised in the form of a narrow canyon that reaches the underlying Miocene gypsum. Besides the intensity of the erosive processes in this valley, there are remains of the H2 infilling level in its catchment (Fig. 9). These accumulation remains are preserved on both sides of the valley and even in a central isolated relict (Fig. 9a). This infill is divided into two units. The first one (Unit 1) is 1.1–1.6 m thick, it lies directly on the Miocene gypsum with an erosive contact (Fig. 9b) and it comprises a monotonous series of horizontal layers of pebbles and compact silty clay of fluvial origin. In its basal part, there is a thin and diffuse level of charcoal fragments that gave a ^{14}C date of 0.85 ky cal BP (Table 1), that is, the late 11th Century AD. Unit 2 is 1–1.2 m thick, it has an erosive base and it is composed of badly stratified silty clay and pebbles, with some very homogeneous sectors. It contains disperse small charcoal fragments, one of which was recovered from the basal part of the unit and dated to the 14th Century AD, 0.6 ky cal BP (Table 1).

4. Discussion

Geomorphological, pedological, and palaeobotanical proxies presented in this paper reflect the environmental and landscape changes occurring in the study area during the last 8.5 ky (Fig. 10). The evolutionary sequence is similar and complementary to other palaeoenvironmental sequences from the CEB.

Pleistocene terraces in other tributaries of the Huerva River, such as Las Lenas and La Morera (Peña-Monné et al., 1996, 2004) remain in hanging positions because of valley incision. Before the aggradation of Unit 1, an erosive stage must have taken place at the end of the Pleistocene and Early Holocene. Peña-Monné et al. (2018) have recently named the first and main Holocene infilling level in valleys in CEB as H1, which comprises three stages: H1A, H1B, and H1C. In different places in the CEB, the oldest dates for these Upper Pleistocene and Holocene accumulations in valleys (H1A) range from 13.8 ky to 7.9 ky

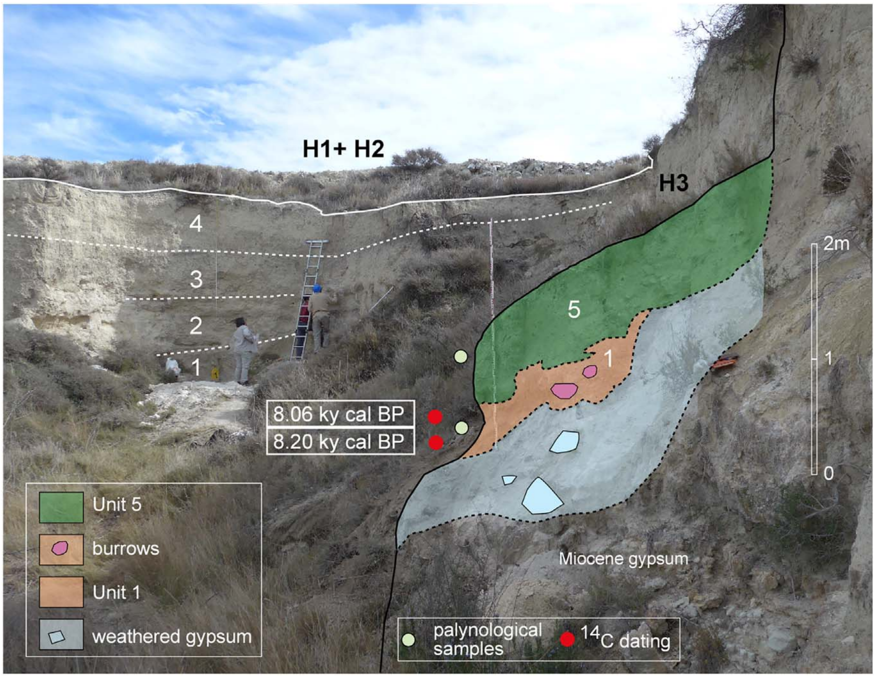

Fig. 8. La Poza B profile, with indication of pollen and ^{14}C sampling contexts.

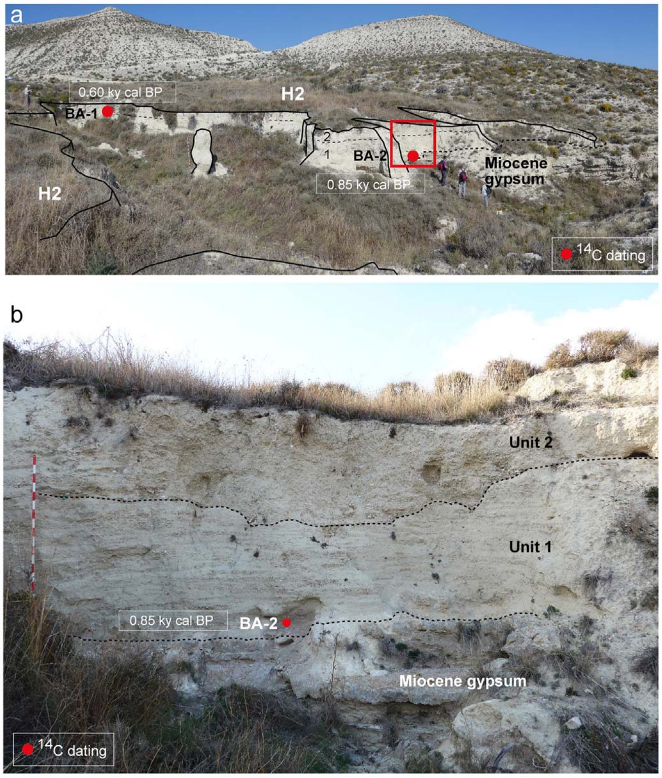

Fig. 9. a) General context of H2 accumulations in La Bajada, ^{14}C samples are indicated. b) Detail of the main profile in La Bajada.

cal BP (Andres et al., 2002; Gutiérrez-Elorza and Arauzo García, 1994; Sancho Marcén et al., 2008). However, the dates obtained from the basal part of most deposits are younger, from 7.1 ky to 4.5 ky cal BP (Constante et al., 2010, 2011; Peña-Monné et al., 1996, 2001, 2004, 2018). It can be argued whether the gap existing between the two groups of dates represents a hiatus in accumulation or indicates that more effort must be made in dating to complete the continuity of the sequence. Whatever the case may be, this first Holocene infilling stage (H1A) began in some places at the very beginning of the Holocene, it became generalized in the Middle Holocene, coinciding with the spread of the Neolithic, and it ended before 4.2 ky cal BP (Peña-Monné et al., 2018).

According to the ^{14}C dates from La Poza A profile (Table 1) and the geomorphologic interpretation of the sequence, Units 1 to 3 represent the H1A accumulation stage (Fig. 11: 1 and 2). Unit 1 formation surely began before 8.3 ky cal BP (date from E16) and probably before 9.5 ky cal BP (date in redeposited material from Unit 1 in E7) and continued uninterrupted until 7 ky cal BP (palaeofire in E13). The origin of the sediment is a combination between in situ pedogenic weathering of Miocene gypsum and marls and, to a lesser extent, colluvium contributions. Under the lithological and climatic characteristics of the CEB, the preservation of a slope deposit from this age is quite exceptional. Besides Unit 1 at La Poza, there is only one previously known slope deposit of this age in the CEB, which is the slope where the Mesolithic hut camp of Cabezo de la Cruz was established near the Huerva River (Peña-Monné et al., 2013).

Under the current semiarid environment, the time span of Unit 1 would seem insufficient for its degree of weathering and pedogenesis, with a well-developed Gypsisol that shows high biogenic activity (worm channels) and solutes translocation (calcite and gypsum). Therefore, it must be considered that environmental conditions were more favourable for soil formation than today. Also, both pollen and charcoal results point to the highest values of the arboreal component (conifers) in the sequence, coherent with the botanical results in the only coetaneous palaeobotanical record in the Huerva Valley (Badal García, 2013; Iriarte-Chiapusso, 2013). Thus, the observed evidences of geomorphologic and edaphic processes, as well as the palaeobotanical results, fit well with the climate conditions established in Mediterranean Iberia for the end of the Early Holocene and the beginning of the Middle Holocene (following the Holocene division of Walker et al., 2012), when warm and moister conditions developed (Carrión et al., 2010). In addition, regional palaeoenvironmental records are congruent with this interpretation. Sedimentological and palynological sequences from southern Central Pyrenean lakes (González-Sampériz et al., 2017), north of our study area, show an increase in humidity and a rise in winter temperatures that resulted in forest expansion between 9.7 and 6 ky cal BP. Similarly, in southern locations of the CEB, thus in the Iberian Range (Moncayo and Albarracín areas), palaeobotanical data from

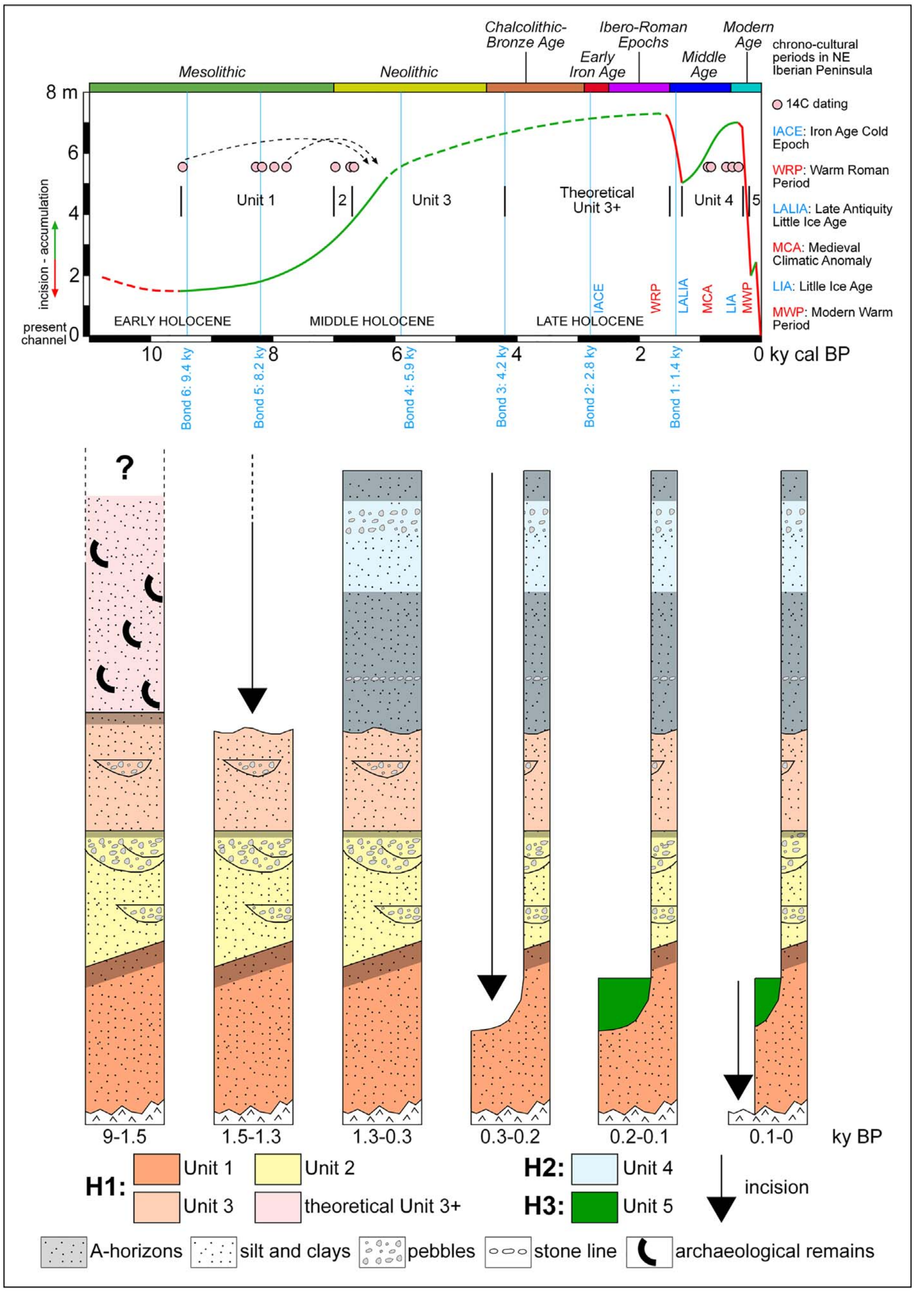

Fig. 10. Graph showing the accumulation and incision sequence in La Poza according to profiles A and B (top). Schematic evolution model of La Poza infill stratigraphy (bottom).

fluvial tufas and lacustrine sequence reconstruction reflect a warm and humid period between 9.5 and 4 ky cal BP (Aranbarri et al., 2014, 2016). Despite some radiocarbon dates obtained in both La Poza A and B profiles pointing to chronologies near the well-known 8.2 ky cal BP event (Bond et al., 1997), the identification of its impact, as well as any other abrupt regionally-recorded climate changes in the Early Holocene (González-Sampériz et al., 2006, 2009, 2017; Pérez-Sanz et al., 2013), has been negligible in our sequence.

In chrono-cultural terms, this Unit 1 belongs to the Mesolithic and the Early Neolithic. In foothills in the Ebro Valley, the first Neolithic evidence at hunter-gatherer sites dates back to 7.8 ky cal BP in Levels V and VI at Peña de las Forcas II (Utrilla and Mazo, 2014). Soon afterwards, ca. 7.5 ky cal BP, Phases 1a and 1b at Chaves Cave were entirely Neolithic (Baldellou Martínez, 2011). A similar sequence was recorded in the Arba de Biel Basin (Montes et al., 2016). This early evidence of Neolithization in the foothills of the Ebro Valley is linked to the last phase at Cabezo de la Cruz Mesolithic hut-camp in CEB (Rodanés Vicente and Picazo Millán, 2013), dated to 7.8 ky cal BP and only 6 km from La Poza.

The charcoal layer that marked the change from Unit 1 to Unit 2 and the pronounced differences in sediments and processes between them indicate an environmental change. As demonstrated in other regional sequences (Gil-Romera et al., 2014), a drier and warmer climate, with abundance of wood fuel in the vegetation composition, is a good scenario for an increase in the frequency and intensity of wildfires, such as the one recorded in Unit 1 in La Poza sequence. The prolonged rising temperatures at the end of the Early Holocene and the beginning of the Middle Holocene (8.3–7.07 ky cal BP) could have led to an increase in evapotranspiration, resulting in a decrease in water availability. Additionally, unevenly distributed precipitation could have had similar effects. Finally, the possibility of a human trigger in this environmental change should be considered. Although it cannot be assured that the fire in Unit 1 was human-induced, there is evidence of the use of fire for forestry management and hunting by other European Mesolithic societies (Crombé, 2016; Evans, 1975; Rankine et al., 1960) and Australian hunter-gatherer aborigines (Bird et al., 2003). Moreover, it is

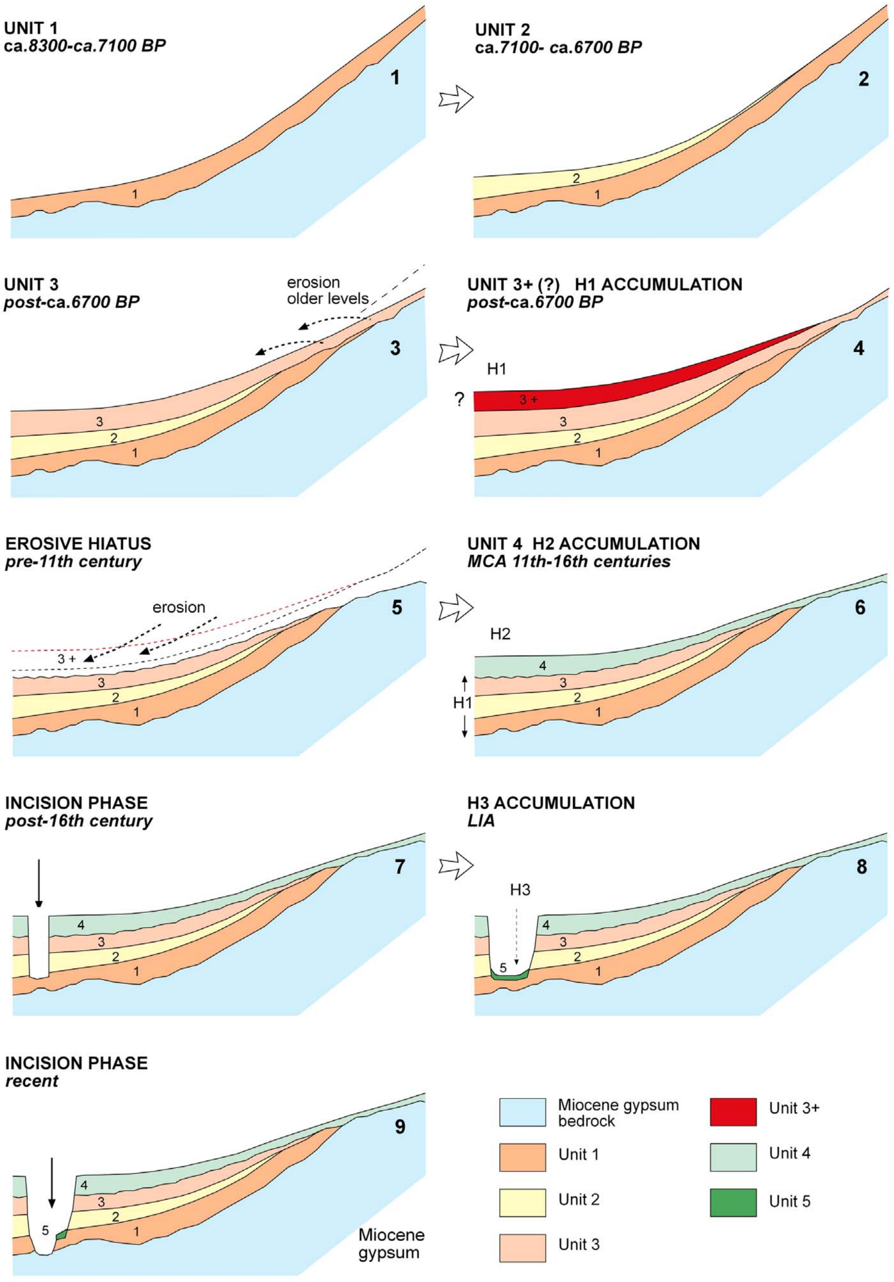

Fig. 11. Holocene evolutionary model for La Poza Valley infill.

significant that the fire in Unit 1 coincidences with the onset of the Neolithic expansion process in the Ebro Valley.

After 7 ky cal BP, both the climatic features and the subsequent occasional fires reduced the biological protection of soil, resulting in an increase in erosion processes and changes in the hydrological activity of the catchment area of La Poza. Former stability was replaced by erosion of the catchment and longitudinal transport of fine and coarse material along the valley. However, it was a low energy flow unable to transport very far the sediments (gravels and pebbles maintain angular shapes) that were deposited in the bottom of the valley forming cross-stratified channels. Different grain sizes in these channels evidence changes in flow energy, probably related to unevenly distributed precipitation during the year. This fluvial accumulation began in the bottom of the valley and gradually covered the foot of the adjacent slopes (Unit 1), burying the burnt Calcic Gypsisol. In this new alluvial context, successive sedimentary inputs continuously renewed the soil in short time lapses. In such conditions, soil development is difficult, such as in the Fluvisol of Unit 2, with a poor A-horizon (E9) above several unstructured C-horizons with different grain sizes. As mentioned above, no pollen is preserved in this soil, and charcoal fragments in the C-horizons seem to be redeposited material from Unit 1. The A-horizon is rich in charcoal and ash from a fire that burnt the vegetation growing in the Fluvisol and nearby slopes 6.7 ky ago (open forest of junipers with probably isolated pines and some shrubs, e.g. Maloideae and Fabaceae).

Unit 2 represents a relatively short time period of ca. 300 years. Its base is dated post-7 ky cal BP (after the fire episode located at the top of Unit 1: E13) and the upper limit at 6.7 ky cal BP (when new fire evidence is recorded: E9). While the sedimentation rate in Unit 1 was 0.05–0.1 cm/y, in Unit 2 it reaches 0.31 cm/y. Thus, an aridity trend is recorded at this time in the area, with reduced vegetation cover combined with a probably unevenly distributed annual precipitation pattern that resulted in short episodes of intense erosion in the catchment of La Poza. González-Sampériz et al. (2017) suggest a similar precipitation pattern after 6 ky cal BP in the southern Pyrenees. Furthermore, next to climatic and particular lithological conditions, the concurrence of anthropogenic pressure on the CEB landscape can be suspected in this period due to the expansion of Neolithic societies. Although the prehistoric archaeological record in the CEB is badly preserved due to intense erosion, evidence of Neolithic occupation in the area has been found in the nearby Huerva Valley (Bea Martínez et al., 2010; Pérez-Lambán et al., 2010).

Unit 3 (Fig. 11: 3) stratigraphically represents the upper part of the main Holocene infill level (H1). Its sedimentation must have begun directly after the fire in E9 (Unit 2), in such a way that the burnt Fluvisol was rapidly buried and preserved. It is therefore reasonable to place the beginning of Unit 3 ca. 6.7 ky cal BP. However, ^{14}C dates from this unit (E8: 7.8 ky cal BP and E7: 9.5 ky cal BP) are inverted and correspond to the chronology of Unit 1. Additionally, the identified charcoal assemblage is almost the same in Units 1 and 3. Moreover, Unit 3 is mainly composed of fine material similar to the gypsum silt of Unit 1. It seems clear that eroded materials from Unit 1 formed Unit 3. The slope deposits from the older unit must have persisted for some time, but progressive deforestation finally led to their erosion and deposition in the valley bottom. The general fine grain size in Unit 3 indicates that La Poza stream possessed little energy during this stage. However, some thin layers of gravel are evidence of more intense ephemeral water flows.

Its duration and ending are more problematic. According only to internal ^{14}C dates from La Poza A profile, it is only possible to ascertain that its upper chronological limit must be before 0.93 ky cal BP, which is the age of the base of Unit 4. Opportunely, regional geomorphologic and palaeoenvironmental information help to determine the age of this unit. Studies of Holocene slope deposits in Peña Enroque in the Huerva Valley, as well as in other reliefs in the CEB and in the Iberian Ranges, identify two main accumulation stages, each of them preceded by a slope erosion phase (Pérez-Lambán et al., 2014). The older of these two generalized slope deposits is named the Bronze-Iron Age slope, as it accumulated in that time, and displays solifluction features that are related to a cold and humid climate. Its formation time spans from shortly after 4.2 ky cal BP to ca. 2.5 ky cal BP. The second slope deposit is much younger and has been related to gelifraction processes during the Little Ice Age (LIA). Today, all these slope deposits are suffering severe erosion.

As stated above, a slope erosion stage in the catchment area of La Poza Valley is compatible with the sedimentary composition in Unit 3. A relationship between the pre 4.2 ky cal BP slope erosion and Unit 3 accumulation can be established on the base of the proximity between Peña Enroque and La Poza and the regional generalization of the erosive stage. Consequently, alluvial sedimentation in Unit 3 might have stopped when the slope erosion stage changed to a slope regularization stage after 4.2 ky cal BP.

If the chronological correspondence between Unit 3 alluvial sedimentation and the slope erosive stage previous to the Bronze-Iron Age slopes is correct, Unit 3 accumulation lasted for ca. 2.5 ky. However, it must be considered that these kinds of alluvial infilling processes are discontinuous, with internal erosive episodes related to concentrated seasonal precipitations, as evidenced by thin channels of gravel in Unit 3. Also, during the final moments of this unit, sedimentation must have slowed down leading to relative stability that favoured the development of an incipient Haplic Gypsisol. However, in comparison with the Calcic Gypsisol in Unit 1, the one in Unit 3 is clearly less structured and bioturbated, as it developed in a shorter time and less favourable conditions.

The contact between Units 3 and 4 is erosive and the A-horizon of the Haplic Gypsisol in Unit 3 is lost. In addition, there is a 3.27 ky time lapse between the proposed age of the former and the ^{14}C date from the lower part of Unit 4 (0.93 ky cal BP in E5). However, the actual time frame of this erosive stage and its intensity must be carefully considered. During this 3.27 ky period, we assume the existence of a hypothetical accumulation (which we name Unit 3 +, Fig. 11: 4) followed by an intense erosive stage responsible for the disappearance of this supposed unit and the A-horizon of the Haplic Gypsisol in Unit 3 (Fig. 11: 5).

Further arguments support this assumption. First, in the regional valley infilling model for CEB, the upper part of H1 infill level reaches the Late Roman Era (ca. 1.5 ky cal BP) with the accumulation of H1B and H1C, which are missing in La Poza A profile. Both of them are well dated in many valleys in the CEB (Constante et al., 2010, 2011; Gutiérrez-Elorza and Peña-Monné, 1998; Peña-Monné et al., 2004, 2014, 2018; Sancho Marcén et al., 2007, 2008): the first one between 4.2 and 2.5 ky cal BP (Chalcolithic, Bronze and Early Iron Age) and the second one between 2.5 ky cal BP and 1.5 ky cal BP (Ibero-Roman to Late Roman). The accumulation rate of H1B and H1C in most ephemeral valleys in the CEB tended to accelerate progressively as a response to human activities (overgrazing, deforestation, agriculture, etc.) and to the rising temperature trend that culminated in the Warm Roman Period (Peña-Monné et al., 2014).

Moreover, just after the beginning of the proposed stability stage that followed the Unit 3 accumulation (post 4.2 ky cal BP), a Bronze Age community (ca. 4.1–3.8 ky cal BP) settled in the archaeological site known as Los Collados, which is very rich in charcoal and pottery fragments. Los Collados settlement was destroyed by intense fire ca. 3.8 ky cal BP and has suffered severe erosion since then. This raises two questions for La Poza A profile interpretation. The first is the absence of correlation between the fire at the settlement and the fire events and dates in the profile. If the fire that destroyed the site was a wildfire affecting the whole area, fire remains would also be expected in La Poza Valley infill. The second is the non-appearance of archaeological materials (pottery and charcoal fragments) in La Poza Valley infill, which should have been transported in the post 2.5 ky cal BP slope erosion and valley infilling stage.

Consequently, Unit 3 + hypothetical accumulation (Fig. 11: 4) would represent H1B and H1C infilling stages and complete the main Holocene infilling level (H1). This unit would contain archaeological remains from Los Collados, the nearby Bronze Age archaeological site. Later, an intense fluvial incision stage would have eroded Unit 3 + and the upper part of Unit 3 (Fig. 11: 5), generating the erosive contact between Units 3 and 4. Generally, CEB valleys underwent an incision stage after Late Roman times (ca. 1.5 to 1.3 ky cal BP) (Peña-Monné et al., 2018).

A relationship between slope and valley processes has already been described in the Huerva Valley (Peña-Monné et al., 2004). In general terms, slope erosion stages correlate with alluvial sedimentation in ephemeral streams in the area, while slope regularization stages are related to stability or incision stages in the valleys. Despite the lack of precise chronological control, a similar pattern can be suggested for Unit 3 in La Poza in relation to Peña Enroque slopes (Pérez-Lambán et al., 2014). Sedimentation in Unit 3 would imply erosion of the nearby slopes (remains of Unit 1). There is a well-known slope erosion stage affecting the whole region prior to or ca. 4.2 ky cal BP. Later, the Bronze-Iron Age slope regularization stage (post 4.2–2.5 ky cal BP) might be related to the decrease in the sedimentation rate and edaphization of Unit 3. Our hypothetical Unit 3 + accumulation would then result from the slope erosive stage that came from Ibero-Roman to Late Roman times (2.5–1.5 ky cal BP). And finally, from Late Antiquity to the Middle Ages, generalization of landscape degradation led to the erosive stage identified in the contact between Units 3 and 4.

After this Late Antiquity incision, in most CEB valleys, new alluvial accumulations (H2 and H3) occupy nested positions inside the incision. In contrast, in La Poza, sedimentation in Unit 4, representative of the H2 phase, continued over Unit 3. This different arrangement in La Poza profile can be explained by its topographical position in the upper catchment area. The main erosive processes causing incision in the area are piping and basal undermining. These begin in lower positions in the gully and move upstream towards the upper parts. This backwards incision had not reached the catchment of La Poza when Unit 4 accumulation began. However, in the meanwhile, other erosive processes such as concentrated runoff could have affected Unit 3.

Unit 4 is the upper part of La Poza A profile and corresponds to the Holocene infilling level H2. Its age is medieval and modern, starting before 0.93 ky cal BP (E5), and it is formed by a succession of buried soils (Fig. 11: 6). The accumulation of fine-grained material that formed E6–E5 must have been slow enough for the gradual edaphization of the sediment that generates A-horizons. Afterwards, sedimentation rate accelerated leaving no time for edaphization of the new sediments (E4). A period of relative stability took place ca. 0.39 ky cal BP, when E3 developed an A-horizon. Later, the water flow was reactivated leaving a layer of gravels (E2) that has the second highest amount of coarse material in La Poza, after the channel in E10. Finally, fine-grained sediment culminates the profile (E1), with the current soil. These three soils in Unit 4 are poorly developed Regosols that have had little time and unfavourable conditions for their evolution. Pollen and charcoal fragments show a vegetation cover similar to the current one, with the increased representation of herbs and shrub communities. It is not possible to establish the precise moment when Unit 4 sedimentation ended, as no dates from E1 are available.

The H2 Holocene infill level is also present in La Bajada profile (Fig. 9), where Units 1 and 2 form a wide accumulation level dated in the Middle Ages, between 0.85 and 0.6 ky cal BP. Most likely, intense human land use and a warmer and drier climate related to the Medieval Climate Anomaly caused this important accumulation. Unlike La Poza sequence, H2 at La Bajada lies directly on the Miocene substratum. This is due to the complete erosion of the previous accumulations, which is explained by the high gradient of this valley.

During the last four centuries, accumulation was no longer the main process in La Poza. A deep incision dug through Units 4 to 1 but did not reach the Miocene substratum (Fig. 11: 7). Then a new accumulation (Unit 5) formed directly on top of the remains of Unit 1, as observed in the La Poza B profile (Fig. 11: 8). This accumulation was related to the Little Ice Age climate variability (Morellón et al., 2012; Saz Sánchez, 2007) and corresponds to the H3 Holocene infill level described in other recent sequences in the CEB (Peña-Monné et al., 2014, 2018; Sancho Marcén et al., 2007). Since then, incision has been the prevailing process and has reached the Miocene substratum (Fig. 11: 9). These rapid incision and accumulation successions evidence the sensitivity of the CEB landscape to climate variability.

5. Conclusions

Considering all profiles recorded, 5 sedimentary units were recognized. The main profile (La Poza A profile) showed a succession of phases of stability with soil formation and others where sedimentary processes were dominant. The earliest sedimentation stages in the valley (Unit 1) started before 8.4–8.1 ky cal BP and continued until a stable period that allowed the formation of a well-developed palaeosol before 7.2–7 ky cal BP under a wetter climate. A shift towards drier conditions allowed the acceleration of sedimentation with the formation of a new sedimentary unit (Unit 2) formed by gravel channels and finally stabilized with a new palaeosol dated to 6.8–6.6 ky cal BP. While Unit 1 is characterized by a stable landscape with relative dense vegetation cover with maximum of conifers, Unit 2 marks a shift towards more slope erosion and, hence, accumulation in the gully bottom as a result of open vegetation. This change can be mainly related to climate conditions, lithological features, and, especially, the onset of the expansion of Neolithic societies in the Ebro Valley. A sedimentary process started to form Unit 3 mainly formed by materials inherited from slope remains of Unit 1, which perhaps were eroded between ca. 6.7 and 4.2 ky cal BP, following the regional model. According to our records, there is an erosive contact between Unit 3 and Unit 4, and the gap represented by the hypothetical Unit 3 + should contain the archaeological remains eroded from the archaeological sites in the area. Unit 4 was dated between 0.97–0.8 and 0.44–0.3 ky cal BP and corresponds to the Middle Ages. A strong incision phase led to the development of a canyon that did not reach the substratum, however a later nested terrace developed (Unit 5) related to the Little Ice Age. In La Bajada profile, Units 1 and 2 lie directly on the Miocene substratum, as previous infills have been completely eroded. This extreme intensity in erosion in La Bajada is due to its high gradient.

From the point of view of the environmental conditions represented by each Unit in the profile, the difference between the basal part and the other units must be highlighted. Edaphic development and vegetation cover in Unit 1 imply stability under favourable conditions on a millennial scale, coherently with ^{14}C dates. The environment during the Early Holocene was characterized by a relatively wetter climate and absence or very little human disturbance of the vegetation cover. The mid and upper parts of La Poza A profile reflect an environment of increasing aridity, probably with seasonal high intensity precipitation, and important anthropogenic pressure. A much sparser vegetation cover was inefficient in preventing soil erosion and therefore the landscape became very sensitive to both the well-known human impact intensification in the Middle and Modern Ages and climatic fluctuations, such as the LIA. Under these conditions, soils had very little time to develop and, therefore, the upper part of La Poza polycyclic soil *sequum* has short-aged poor soils.

The interdisciplinary approach to the study of the earliest Holocene sequence in the CEB has furthered our knowledge of its palaeoenvironmental evolution and the regional responses to global factors. Comparison with other case studies also allows gaps to be filled in the evolutionary sequence of the CEB. On the other hand, the detection and explanation of differences between case studies highlights the importance of local factors such as topography or local settlement history. This information from La Poza and the CEB enhances our understanding of Western Mediterranean landscape evolution, which is both necessary for historical explanations and currently an important issue due to its fragility.

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