HOLOCENE ALLUVIAL SEQUENCE IN THE VAL DE ZARAGOZA (LOS MONEGROS) IN THE PALAEOENVIRONMENTAL CONTEXT OF THE EBRO BASIN (NE SPAIN)

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ABSTRACT. *Flat-bottomed valleys formed by Holocene fills are the most characteristic landforms in the center of the Ebro basin. This paper analyzes, within a regional framework, a small fluvial basin located in the north of the Alcubierre Range. Three Holocene morphosedimentary units (H1-H3) and a sub-functional level (H4) are identified. These units are representative of the regional geomorphological evolutionary process in the Ebro basin. New chronological insights on climate and landscape management are provided by a study of the Bastarás weir, a construction made for water flow management during the Little Ice Age (LIA). The integration of Val de Zaragoza radiocarbon datings into the regional framework enables the authors to identify the main formation stages, as well as the influence of climatic and human factors on its evolution. The intensification of human pressure in the territory is reflected in a progressive increase in sediment accumulation rates in the valleys, peaking during Roman times and the Little Ice Age.*

Secuencia aluvial holocena de la Val de Zaragoza (Monegros) en el contexto paleoambiental de la cuenca del Ebro (NE España)

RESUMEN. *Los valles de fondo plano formados por rellenos holocenos constituyen los paisajes más característicos del sector central de la cuenca del Ebro. En este trabajo se analiza una pequeña cuenca fluvial localizada en el norte de la Sierra de Alcubierre, en la que se han identificado tres unidades morfosedimentarias holocenas (H1-H3) y un nivel subfuncional (H4), que son representativos de la evolución geomorfológica regional de la Cuenca del Ebro. Uno de los aspectos más relevantes del*

valle lo constituye el azud de Bastarás, construcción realizada durante la Pequeña Edad del Hielo para el aprovechamiento del agua, que aporta nuevos datos cronológicos sobre dicha época y acerca de la gestión del territorio. La integración de las dataciones radiocarbónicas obtenidas en la Val de Zaragoza en un marco regional ha permitido precisar las principales etapas de formación de los valles de fondo plano, así como la importancia de los factores climáticos y humanos en su evolución. La intensificación de la presión humana sobre el territorio queda reflejada en un progresivo aumento en las tasas de acumulación de sedimentos en los valles, alcanzando sus picos máximos en Época Romana y en la Pequeña Edad del Hielo.

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1. Introduction

Holocene sedimentary records are of great importance for understanding environmental changes related to climatic fluctuations and human impact on the landscape. Studying these records requires several interdisciplinary tools and analytical methods to produce paleoenvironmental reconstructions and evolutionary models, such as those used in various geoarchaeological studies (Peña Monné *et al*., 2005; Peña-Monné and Sampietro-Vattuone, 2014). Drylands are most suitable areas for this type of study, because of their environmental fragility and the quick response of geomorphological processes to landscape changes. Thus, it is not surprising that pioneering research of geoarchaeological interest was carried out in the Mediterranean area (Vita-Finzi, 1969; Pope and Van Andel, 1984; Brückner, 1986; Bintliff, 2002; Butzer, 2005).

The Holocene records most commonly used for paleoenvironmental reconstructions in NE Spain are valley bottoms and slope accumulations. At the center of the Ebro depression, the bottoms of the fluvial valleys surrounding the city of Zaragoza (Figs. 1a, b) have a flat morphology due to Holocene infilling processes. These flat-bottom valleys are locally known as *vales* and are carved on an evaporitic substratum made up of alternating gypsum, marl and glauberite beds (Salvany *et al*., 2007).

These lithologies show a fast geomorphological response to environmental changes caused by natural or anthropogenic forces. For this reason, the *vales* of the middle section of the Ebro Basin were the focus of several geomorphological studies and paleoenvironmental reconstructions. In this central sector of the Ebro basin, the studies has focused on the Huerva and Ginel Rivers and Valmadrid flat-bottom valley, all of which are right side tributaries of the Ebro River (Van Zuidam, 1975;

Burillo *et al.*, 1985; Soriano and Calvo, 1987; Soriano, 1989; Peña Monné, 1996; Peña Monné *et al*, 1993, 1996, 2001, 2004; Arauzo and Gutierrez, 1994; Peña Monné *et al.*, 2014). Secondly, several studies were based on the *vales* that descend to the left margin of the Ebro River traversing the gypsum scarp (Constante *et al.*, 2006, 2009, 2010, 2011; Constante and Peña-Monné, 2009) and to the north of Zaragoza around the village of Leciñena (Sancho *et al.*, 2007a). Peña Monné *et al.* (2014) reviewed these studies and synthesized the Holocene evolution of the center of the Ebro depression. Finally, the infilled-valleys of Bardenas Reales (Navarra) that are located 100 km to the NW of the study area, yield data about regional Holocene evolution (Peña Monné *et al.*, 2006; Sancho *et al.*, 2007b, 2008) and provide information that is used here as complementary data.
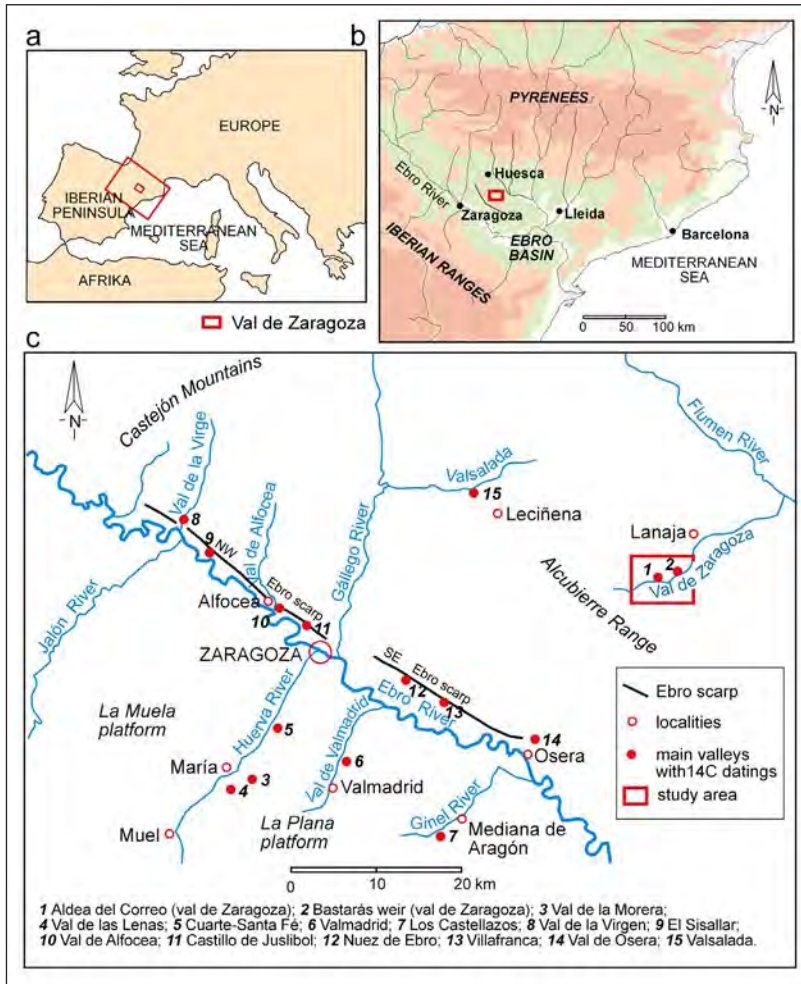

Figure 1. a) General location map; b) Location map of the main dated valleys and archaeological remains of the Ebro basin. Location of Val de Zaragoza in the regional context.

There is no synthesis that covers this geographical area in a single evolutionary model so far. In this study, the Val of Zaragoza, a secondary valley located to the north of Los Monegros, to the NE of Zaragoza city, provides an example and analog to synthesize the evolution and processes involved in the development of flat-bottom valleys. Besides, its geological substrate (limestones and marls) different from that previously described (basically gypsum), it is also higher than average, has north orientation and higher than average humidity in the central Ebro basin (average annual precipitation of about 400-450 mm against 300-350 mm) give a completely different microenvironment and offers new data about the climatic influence on the evolution of Holocene valleys. Moreover, the existence of a remarkable weir for irrigation in the middle section of the valley, built during the 19th century, enabled establishing its relationship with the wetter climatic periods of the LIA. In addition, we analyzed the influence human interference in the geomorphological dynamics of the valley and the responses in terms of aggradational and erosive processes.

2. Study area

The Val of Zaragoza is in the north of the Ebro Tertiary Depression, in the Los Monegros area, and close to Lanaja (Huesca Province, Spain) (Fig. 1c). The topography of Los Monegros is dominated by the Lanaja and Alcubierre Ranges (832 m at San Caprasio Mount) (Fig. 2), which form an elongated NW-SE oriented alignment. These ranges are the watershed limit between the southern slopes that directly flow to the Ebro River and the tributaries of the Flumen and Guatizalema rivers coming from the Pyrenean piedmont.
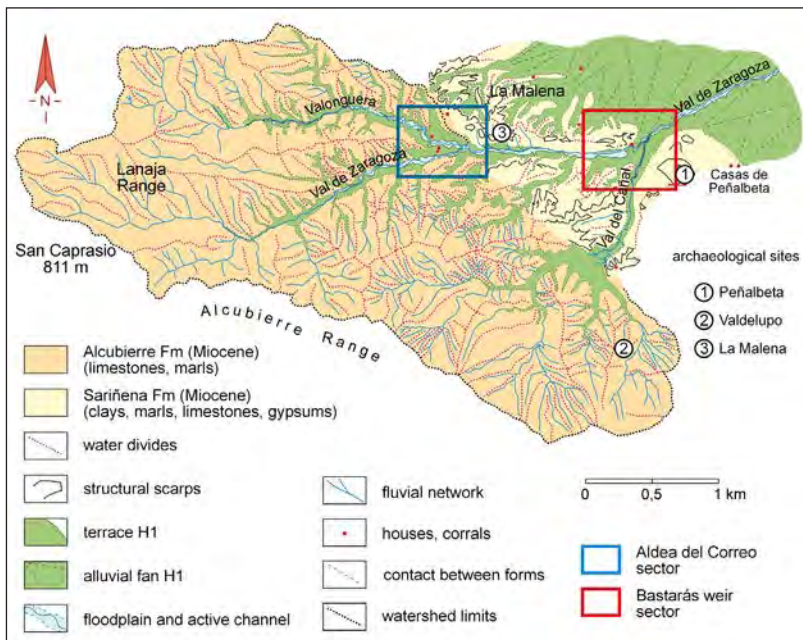

Figure 2. Geological and geomorphological map of the Val de Zaragoza basin, location of the detailed maps of the studied areas (Figs. 4 and 6).

This section of the Ebro basin is composed of Miocene continental sediments from two geological units (Fig. 2): Sariñena Fm and Alcubierre Fm (Quirantes, 1978; Riba *et al.*, 1983). Their chronostratigraphy correspond to the Aragonian and Vallesian stages (Costa *et al.*, 1998). The units are part of the Tecto-sedimentary units T5 and T6 proposed by Alonso-Zarza *et al.* (2002). The Alcubierrre Fm emerges at the head and middle section of the Val de Zaragoza and it is composed of limestones and marl-limestones. The Sariñena Fm consists of detrital materials, with a predominance of sandstones and marls and some interbedded limestones. In the final reach, the valley runs along a deep canyon excavated on dark gypsum deposits of Sariñena Fm.

These geological units have a sub-horizontal stratification and form narrow stepped platforms and mesas eroded by a dense incised drainage network. The headwaters of Val de Zaragoza, Valonguera and Val del Cañal are in the northern slope of Alcubierre and Lanaja Ranges, descending through their piedmont formed by one of the previously described platforms and some Pleistocene glacis remnants where Holocene valleys (or "*vales*") are entrenched (Fig. 3).
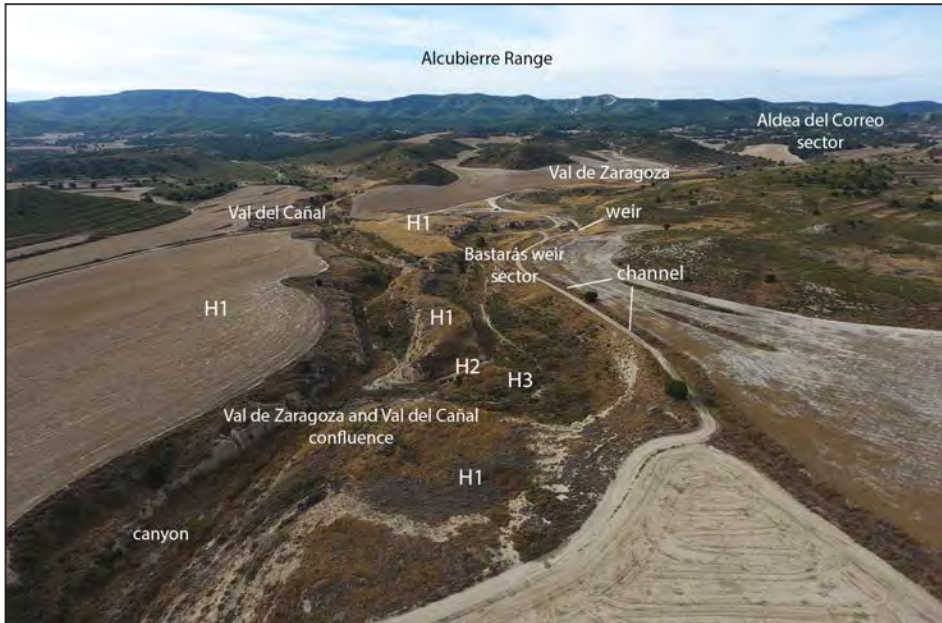

Figure 3. Aerial photograph of Val de Zaragoza from the Val del Cañal confluence looking the bottom the Alcubierre Range.

The Val de Zaragoza climate is continental Mediterranean with semiarid characteristics; annual average precipitations are between 400-450 mm, falling in spring and autumn. Mean annual temperature is around 15ºC. Prevailing NW winds (*cierzo*) tend to dry the soils. The area has a major water deficit conditioning the development a poor plant coverage, and is also influenced by secular human impact. The structural reliefs are characterized by open forests

of *quejigos* (*Quercus faginea*), holm oak (*Quercus ilex*), sabin juniper (*Juniperus thurifera*), and pine (*Pinus halepensis*), accompanied by scrubs; rosemary (*Rosmarinusofficinalis*), thyme (*Thymus vulgaris*), and sage (*Salvia lavandulifolia*). Valley bottom soils are rich in sodium, so *albardín* (*Lygeumspartium*) and tamarix (*Tamarix africana* and *Tamarix gallica*) are abundant near ephemeral water courses. Any irrigation channel (Monegros Channel) is close enough to permit irrigation agriculture in this part of the inner piedmont.

Vales belong to a type of ephemeral streams that are named *ramblas* or *rieras* in the Mediterranean region. Their main characteristic is that for most of the year they remain dry, with flows linked to sporadic rains. The current climate makes it difficult to believe that water one regularly flowed in these streams or *vales*. However, the presence of a weir at Val de Zaragoza indicates that the situation differed in the recent past. At some point, it was possible to retain and divert water for irrigation, which implies a higher precipitation regime in this area of the Ebro Depression.

From the perspective of human occupation, the temporal and spatial archaeological knowledge of Sierra de Alcubierre and Los Monegros area is not homogeneous. Some extensive surveys showed significant occupation from the Neolithic to the Roman Epoch, and so, the landscape was under a strong and continuous human pressure. Several archaeological sites with differing chronologies are known around the Val de Zaragoza (Domínguez *et al.,* 1984; Giral Royo, 2014) (Fig. 2) and these include Peñalbeta with Neolithic remains, Valdelupo belonging to the Final Bronze-Iron I, and La Malena, the most important settlement in the area. The occupation of La Malena dates back to the Iron Age, with important settlements from the Iberian Epoch, Roman Republic and Imperial Roman Periods, covering the 5th century BC to the 5th century AD. A set of Iberian and Roman coins was found in this settlement. The presence of these archaeological sites at the Val de Zaragoza could be related, as evidenced by its name, to the fact that it was the natural route for traversing the ranges from Zaragoza city to the piedmont of the Alcubierre Ranges. The Aldea del Correo (Post Village) served the communications of the Camino Real (King's Road).

3. Methodology

A geomorphological map of the Val de Zaragoza basin was made, as well as two detailed maps of the areas with the most relevant Holocene accumulations. The main reliefs and Holocene sedimentary records are represented on this map, following the methodology proposed by Peña Monné (1997) for geomorphological cartography, and another more recent bibliography (Peña Monné *et al.*, 2004; Peña Monné *et al.*, 2014). The cartography was made using topographic maps (1:25,000) of *Instituto Geográfico Nacional* (Spain), aerial photographs of the Interministerial Flight from Spain (1:18,000), orthoimages from *Servicio de Información Territorial de Aragón* (2012), and images from Google Earth (2013). The longitudinal and transversal profiles of the valley and their accumulation levels were made using the GPSs Trimble Geoexplorer GNSS and Garmin Montana 650.

Intensive surveys were made on the Holocene accumulations and surrounding areas. These accumulations are typologically classified by their relative chronological value and the intensity of the human impact on the area. Moreover, several charcoal samples were taken for radiometric dating at Beta Analytic (Miami, USA), Arizona University (USA), and Direct AMS (USA). Radiocarbon datings were calibrated using Oxcal 4.2 software with the INTCAL13 curve, considering one sigma. In addition, the datings from the Val de Zaragoza were compared with those of other valleys in the central Ebro basin using the same calibration criteria. However, in the final representation, the middle point of each calibration BP was considered.

The wood charcoal analysis was made at *Departamento de Ciencias de la Antigüedad*, at the University of Zaragoza. A metallographic dark/bright field incident-light microscope (Leica DM2700M) with magnification factors of 100 to 630x was used. Photographs were taken with a coupled digital camera using LAS V4.10 software. The study followed the standardized anthracological methodology (Vernet, 1973). Each fragment was manually broken and the anatomical patterns of each wood species were observed along three anatomical sections: transversal (ST), radial longitudinal (SLR), and tangential longitudinal (SLT). Botanical identification was possible by referencing wood anatomy atlases for both non-charred (Schweingruber, 1990; Garcia Esteban *et al.*, 2003) and charred wood (Vernet *et al.*, 2001), together with the laboratory reference collection.

4. Results

The headwaters of the Val de Zaragoza basin is located at the top of Alcubierre, Range the highest point being the summit at Mount San Caprasio (832 m). This area, known as Lanaja Range, has developed a relief compartmentalized by the river network with narrow ridges of Miocene limestones (Fig. 2). The drainage is W-E, with two main sections: Val de Zaragoza proper and Valonguera, which converge in the middle course at Aldea del Correo reach, where extensive deposits are observed (Fig. 2). The drainage system presents a rectilinear layout, oriented in a W-E direction, at the foot of La Malena reliefs, where it receives tributaries from small southerly basins. This channel converges with the Val del Cañal (Figs. 2, 3) at the Bastarás weir. From this point downwards, the *val* is incised on coalescent alluvial fans (Fig. 2). A deep incision characterizes the lower section of the river, from Bastarás weir up to Lanaja, Finally, the *val* converges with the Flumen River 12 km downstream.

Most of the valleys have infilled flat bottom morphologies due to slope degradation processes. A later incision affected part of their fill, producing a narrow entrenchment of vertical walls and slightly sinuous channels, with meanders in some places (Fig. 3). The incision was formed by piping processes, which favored the headward erosion upstream and laterally with small arched headwaters or amphitheaters due to sediment collapses. This process was accelerated by sediment sodicity, which potentiated circulation and pipe formation hypodermically. As in the other *vales* analyzed, the incisions evolved with lateral collapses enhanced by undermining of the *val* margins (Peña Monné, 1996; Peña Monné *et al.*, 2004).

Later recurrent aggradation and downcutting periods developed lower terraces that are only identifiable in the less eroded sections. This sequence of stepped alluvial surfaces was also identified in other *vales* of the Ebro basin by the latter authors. They are known as level N3 (the main and oldest level), and N2 and N1 (the most recent ones). In some areas, it is possible to find a N0 level in an even lower position, close to the river thalweg (Peña Monné *et al.*, 2004). In this work, these levels are named H1, H2, H3, and H4, i.e., numbered from the oldest to the most recent. These terraces are connected with slope deposits towards the val margins. The morphology is differentiated into terraces (t) or slopes (s), as they appear in the profiles and maps in this paper.

The confluences of the Valonguera (Aldea del Correo sector) and Val del Cañal (Bastarás weir sector) into the Val of Zaragoza hold the thickest Holocene accumulations and represent the most interesting reaches (Figs. 2, 3): The following descriptions focus on these two points.

4.1. Aldea del Correo sector

The area of confluence between Val de Zaragoza and Valonguera is one of the widest reaches with Holocene accumulations, as shown in the geomorphological map (Fig. 4). The main level (H1) forms large and wide fluvial terraces at both margins and its deposit reaches 8 m in thickness, offering a complete sedimentary sequence.
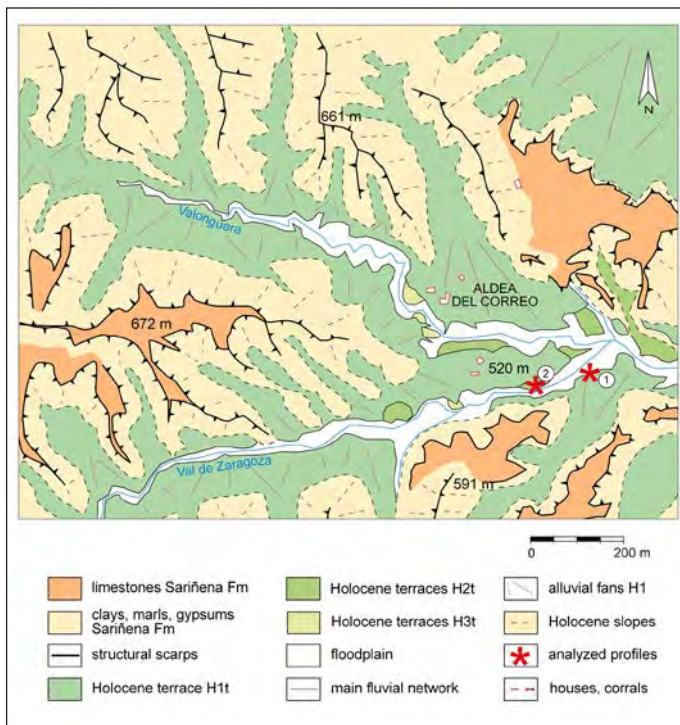

Figure 4. Geomorphological map of Aldea del Correo sector.

Figs. 5a and 5b show the 8,35 m thick stratigraphic profile of the H1 terrace deposit at point 1 in Fig. 1c, and located on the left margin of Val de Zaragoza. The profile is a relatively homogeneous detrital series composed of two main sequences. The lower one is composed of limestone gravels at the base (A), followed by a 2.3m layer of sands and clays with some interbedded gravels (B) and a paleosoil (C) (Fig. 5a). A charcoal sample (VALCO-3, Table 1) was taken from this paleosoil and dated at 4090 ± 29 ^{14}C yr BP (4785-4526 cal yr BP). The upper sequence is made up of 3 m thick sand and clay unit (D) with similar sedimentological characteristics as unit B. It is overlaid by a 2 m thick unit (E) of gravel beds with some calcareous blocks and interbedded channel structures that evidence an intense and dynamic activity in this upper sequence. From a morphological point of view, gravel channels are competent beds that resist erosion and develop ledges while sand and clay beds form cavities and chimneys due to piping and surface runoff processes (Fig. 5b).
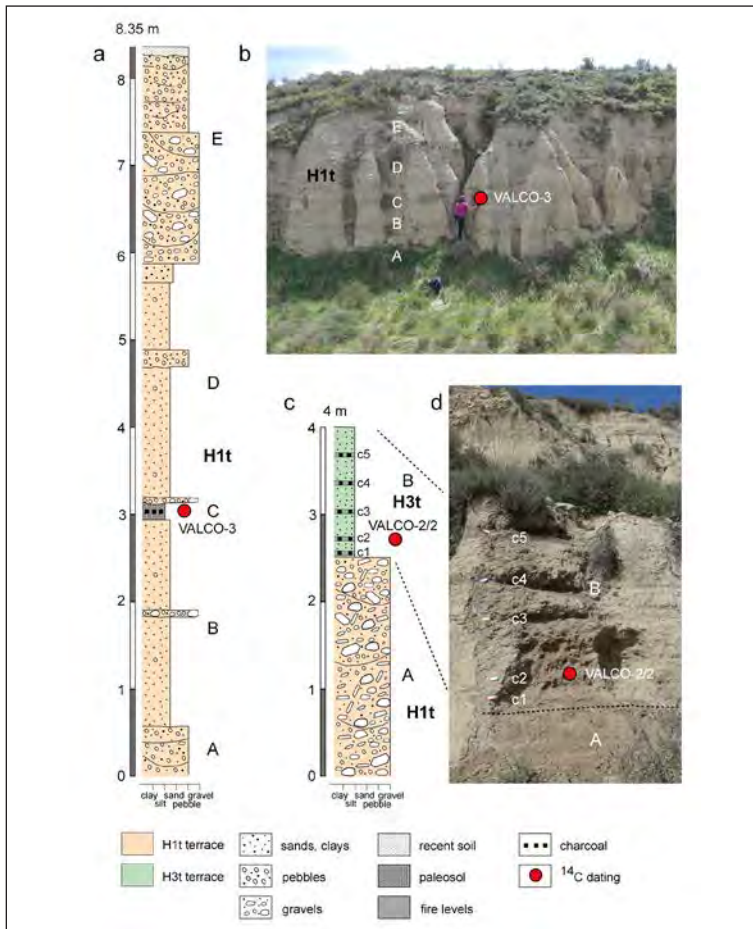

Figure 5. Stratigraphical profiles of Aldea del Correo sector: a) profile and b) photograph of the H1 terrace; c) profile and d) photograph of the H1-H3 terrace fills.

Table 1. Radiocarbon datings.

Field code	Laboratory reference	Material	¹⁴C yr BP	Cal yr BP	Cal yr BC/AD (2 σ ranges)	Cultural period
VZ-06	BETA-347452	Charcoal	4160 ± 30	1σ: 4821-4628 2σ: 4829-4581	1σ: 2872-2679 BC 2σ: 2880-2632 BC	Bronze Age
VZ-04	AA108298 X29002	Charcoal	4153 ± 30	1σ: 4820-4621 2σ: 4826-4580	1σ: 2871-2672 BC 2σ: 2877-2631 BC	Bronze Age
VZ-02	BETA-347451	Charcoal	1970± 30	1σ: 1948-1882 2σ: 1994-1865	1σ: 2-68 AD 2σ: 45 BC-85 AD	Roman Period
VALCO-3	D-AMS 010947	Charcoal	4090 ± 29	1σ: 4785-4526 2σ: 4808-4449	1σ: 2836-2577 BC 2σ: 2859-2500 BC	Bronze Age
VALCO-2/2	D-AMS 010948	Charcoal	100.16 ± 0.36	1σ: 251-35 2σ: 254-32	1σ: 1699-1915 2σ: 1696-1919	LIA

Radiocarbon ages were calibrated to 'calendar' ages by using Oxcal v4.2.4 Bronk Ramsey (2013); IntCal13 atmospheric curve (Reimer et al., 2013).

On the right margin of the same incision, H3t and H2t are preserved forming discordant steps unconformably lying on 2,4 m thick channel gravels belonging to H1t (Figs. 4 and 5c, unit A). In one of the outcrops (point 2, Fig. 4), H3t deposits consist of 1.5 m thick alternating sandyclay and highly carboniferous layers (c1 to c5) (Figs. 5c, d). These carboniferous layers seem to be composed of materials eroded from nearby areas that burned periodically. A recent radiocarbon date of 251-35 cal yr BP was obtained from layer c2. Despite the lack of precision of this dating, this accumulation is clearly related to the Little Ice Age.

Samples from carboniferous c1 to c5 were taken for anthracological study and only the oldest one (c1) was sterile. A total of 175 charcoal fragments from layers c2 to c5 were analyzed, among which at least six taxa were documented (Table 2). The entire sequence is dominated by the presence of Aleppo pine (*Pinus halepensis*). It was not possible to observe all the necessary features in all the fragments due to their small size or poor state of conservation. Therefore, different determination levels were established: *Pinus* sp., *Pinus* cf. *halepensis*, *Pinus halepensis/pinaster* and even undetermined conifers. All of these fragments probably belong to this taxon and *P. halepensis* is also the only clearly determined conifer in the record. In c5 it was possible to only identify *P. halepensis* while in the other layers this conifer is accompanied by other less representative taxa. Evergreen oaks and helm oaks (*Quercus coccifera/ilex*, respectively) are present at all layers except c5, were Aleppo pine is the only identified taxon. Other less climate representative *taxa*, such as *Rosaceae* (c2 and c4) and probably the genus *Pistacia* (cf. *Pistaci*a sp.) (c3), were also documented. The record points to an open Mediterranean landscape similar to the modern landscape. The presence of two deciduous oak fragments (*Quercus* sp. deciduous) in the c4 layer is remarkable, and reveals high taxonomic variability and is possible evidence of some environmental humidity.

Table 2. Results of charcoal analyses.

Level	c5	c4	c3	c2
Depth (cm)	30	66	91	130
Bark	1	2	5	3
Indeterminable conifer	-	-	1	1
Pinus halepensis	49	38	33	16
Pinus cf. *halepensis*	-	-	3	-
Pinus halepensis/pinaster	-	-	1	-
Pinus sp.	-	4	4	3
cf. *Pistacia* sp.	-	-	2	-
Rosaceae Prunoideae	-	1	-	-
Quercus coccifera/ilex	-	1	1	1
Quercus sp. deciduous	-	2	-	-
Rosaceae Maloideae	-	2	-	-
cf. Rosaceae Maloideae	-	-	-	1

From the taphonomic point of view, the size of the charcoals varied from small branches (2 mm) with *cambium* and bark to large fragments of weakly curved growth rings suggesting that they come from big branches and trunks. All samples showed bark and several fragments are affected by vitrification.

4.2. Bastarás weir sector

This area that also shows extended Holocene deposits, is located in the lower meandering reach of Val de Zaragoza at the confluence with Val del Cañal. The infilling deposits are deeply incised leading to a narrow canyon downstream to Bastarás weir (Figs. 3, 6a). The dynamics and recent evolution of this stream reach was strongly controlled by the construction of a weir and other irrigation works (levees, canals, water breakers, and walls) at the beginning of the19th century (Fig. 6a).

The Bastarás weir was built to retain and redirect the sporadic flow waters of the Val de Zaragoza stream for the irrigation of the lands of the Bastarás property, near Lanaja. The weir caused the retention of a large amount of sediment following its construction, favoring aggradation upstream of the dam, and the erosion of the channel deposits downstream generating a canyon that reaches the bedrock. This phenomenon distorted the basal level of the stream channel on both sides of the weir, which must be considered when analyzing terrace surfaces profiles. Similarly, the meander located upstream of the weir was modified by the construction of slightly oblique earth levees on the right margin to direct the flow to the weir (Fig. 6a). For this reason, erosion has focused on the left margin giving way to prominent scarps. The geomorphological cartography (Fig. 6a) enables identifying three stages present at Aldea del Correo area (H1 to H3), with stage H1 being much more extensive than

the others. Moreover, the Val de Zaragoza longitudinal profile (Fig. 6b) shows the general continuity of H1 level, with an average gradient of 18.3 %, the discontinued presence of levels H3 and H2, and the stream gradient rupture that the weir generates. The location of the four studied profiles described below is shown with numbered asterisks in Figs. 6a, b.
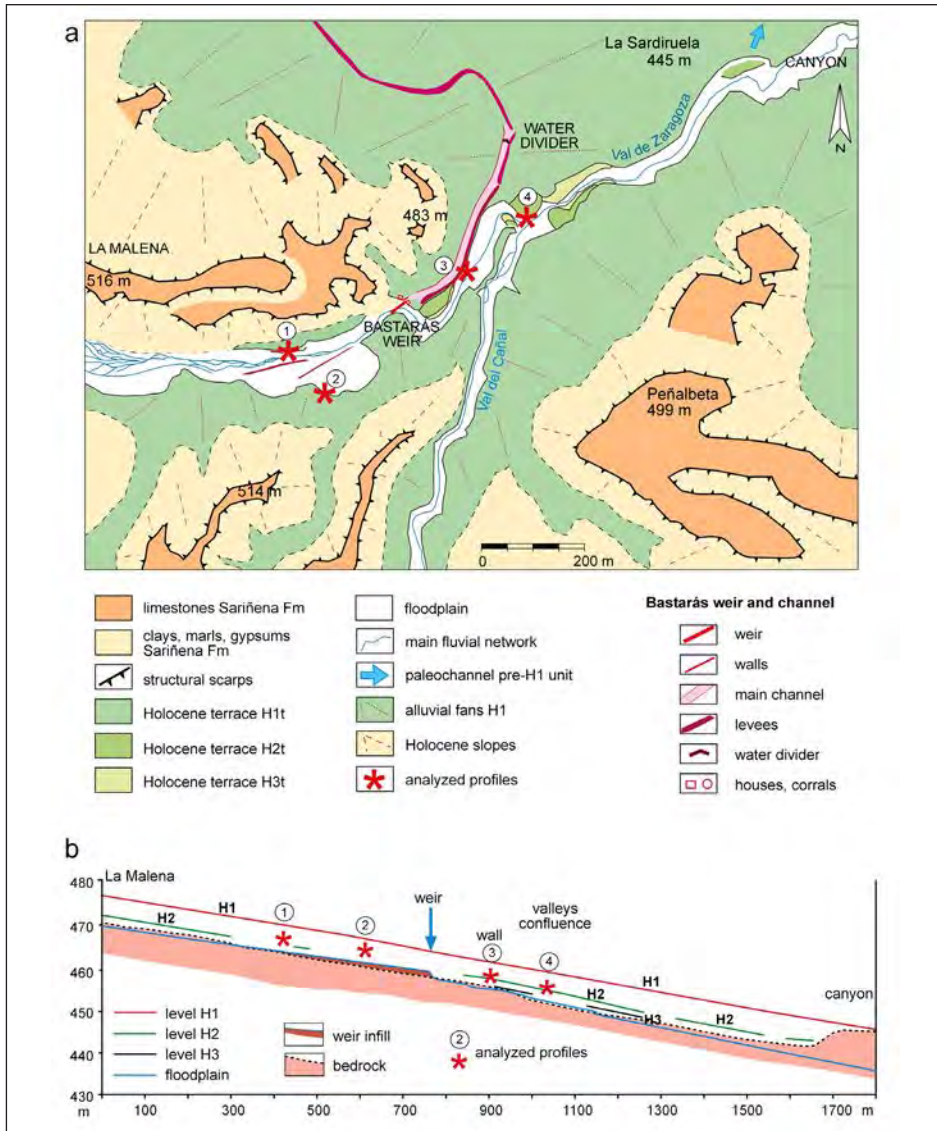

Figure 6. a) Geomorphological map of the Bastarás weir sector; b) longitudinal profile of Holocene levels H3, H2, and H1, with the situation of the four profiles analyzed in the weir of Bastarás sector. The infill and incision induced by the weir is indicated.

Upstream of the weir, two long outcrops are exposed on both margins of the river course (Fig. 7), without reach the bedrock, showing the complete H1 sequence, as well as the sedimentary and morphological characteristics of stage H2. On the left margin, profile number 1 (Figs. 6a, b) is located in a 150 m long stream scarp that displays 2,6 m thick H1 deposit unconformably overlying by 0,4 m thick H2 terrace fill (Figs. 7a, b), without reaching the Miocene substrate. Form base to top, It is possible to identify the following units: (1) Unit A is made up of limestone gravel channels, with some interbedded sandy layers, 1 m thick accumulation of sand and clay, and 0.5 m of channel gravel *facies*. A charcoal sampled at the base of the profile taken from a sand layer was dated at 4821-4628 cal yr BP (VZ-06, Table 1); (2) The next section (B), is 10-20 cm thick and an almost continuous dark layer composed of sediments carried from upslope, containing numerous fragments of charcoal and ashes (unit B), that was also observed on the right margin of the stream with much more continuity; (3) 0.8 m of sandy clay sediments with dispersed limestone gravels (unit C) that are truncated by 0.9-1 m thick H2 deposits. The slope sediment developed at the foot of the nearby structural reliefs, mainly comprises fine sediments and ceramic fragments of different times (Roman, Medieval). This post-medieval times sediment covers the surface of almost the entire H1 unit. Further north, unit H2s becomes thicker and descends to laterally link and overlie H2t (Figs. 7a, c). This last unit is composed in this sector of limestone blocks and gravels, which are badly stratified and little rounded, with almost no imbrication.

The second outcrop (number 2, Figs. 6a, b) is located in a 200 m long meander scarp on the right margin of the Val de Zaragoza behind the earth levees used to divert the waterflow to the Bastarás weir (Fig. 7d). Six profiles were described but only the most representative one was selected for this paper (Fig. 7e). The profile consists of 2.35 m thick, compacted sandy loam sediments, with columnar shape especially in the lower section and partly related to piping and rilling processes (units A and C) with an interbedded 10-20 cm dark layer (unit B), also formed by ashy materials from burned vegetation. This sedimentary package ends with a a thin gravel bed that, gives rise to a gravel pavement with biological crust and whose matrix is highly affected by the water erosion and aeolian deflation. The profile presents a large number of archaeological materials, especially in unit A (Fig. 7e). Most of them belong to the Imperial Roman phase coming from La Malena archaeological site (1st-5th centuries AD), and Iberian and Roman fragments with black varnish from the 2nd or 1st centuries BC. The most abundant fragments are of latter *Terra sigillata* from Spain and Africa. Metallic objects were also found, such as a fragment of lead, probably related to a hydraulic structure of La Malena, and a bronze As of Domitian coin, struck in Rome in 85 AD, classified as RIC II 297 (C) (Mattingly and Sydenham, 1968).

The whole profile has abundant charcoal fragments, especially a layer located 25-30 cm below unit B, where Roman potsherds were also observed. The layer was dated to 1948-1882 cal yr BP) (VZ-02, Table 1) and is chronologically coherent with the coin and ceramic fragments.
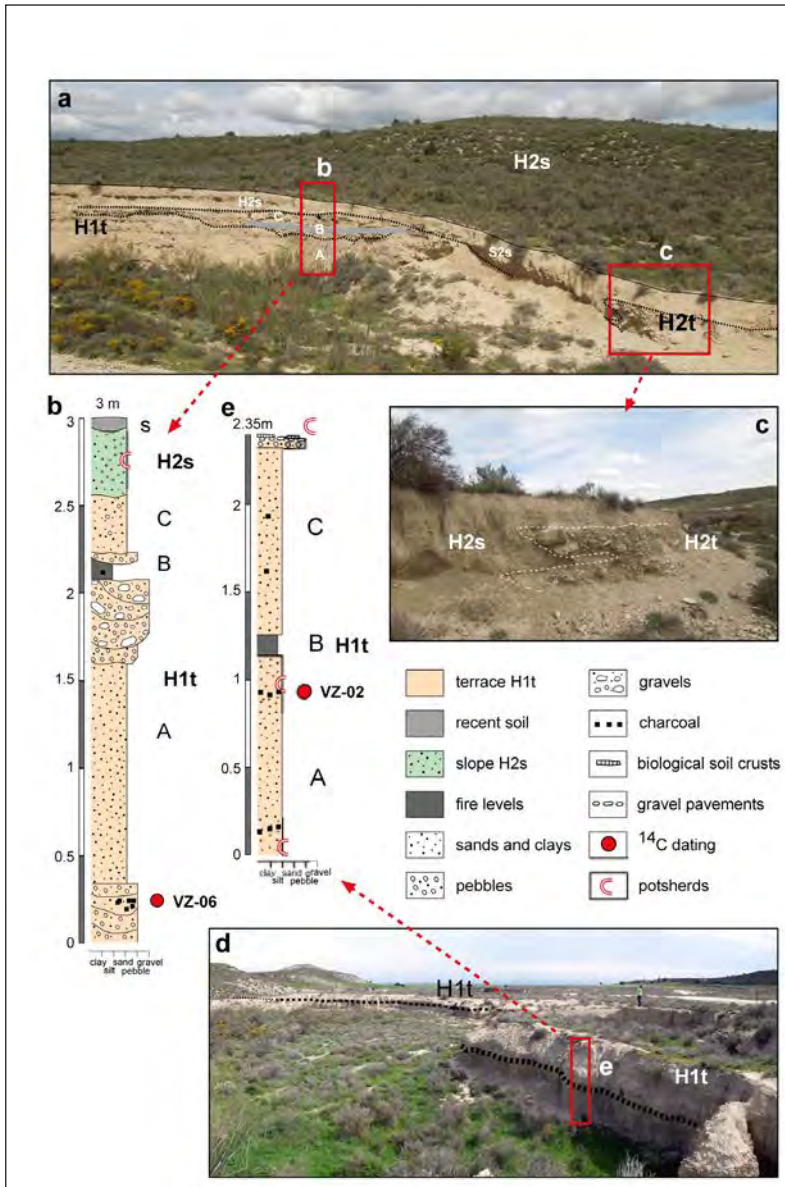
Figure 7. Stratigraphical profiles of Azud de Bastarás sector: a) general view of the outcrop on the left margin of the valley with the position of the analysed profiles (b and c); d) view of the outcrop on the right margin of the meander; e) location of the analysed profile.

In the Bastarás weir and its channel, the levels pointed upstream are present. The stone walls that led to the channel reinforce the front of H1 level, and two small houses used for managing the weir were built above this accumulative level (Fig. 8a). The weir

that was constructed in a 90º meander turn, was built out of sandstone vertical blocks on which some iron rails were placed to be used as guides for wooden planks to close the water flow (Lasaosa, 1997) (Fig. 6). The channel was excavated at H1 level, which in this section reaches over 4 m in width. It was reinforced with an earth levee on its right margin by accumulating the excavated materials (Fig. 8b). This levee was necessary to protect the artificial channel from the eventual erosion and migration of the Val de Zaragoza (Fig. 6).
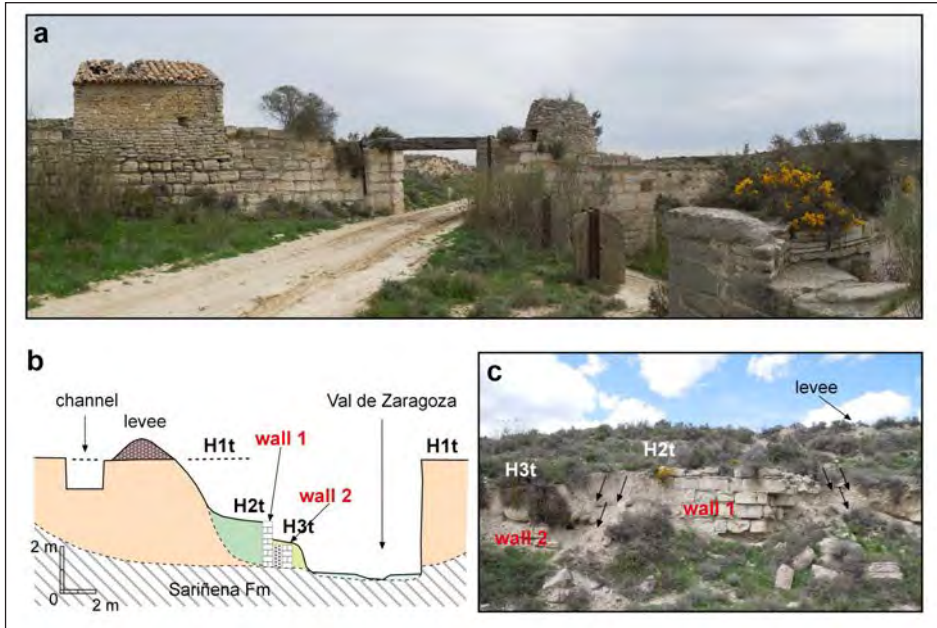

Figure 8. a) General view of the Bastarás weir and the channel begining; b) H1 accumulation with channel position, the lateral levee, and the fence walls (walls 1 and 2) related to H2 and H3 levels; c) detail of the wall position and location of H2 and H3 accumulations.

The dammed basin only included the Val de Zaragoza stream and its tributary, the Valonguera (16.84 km²), and exclude Val del Cañal (8.21 km²) (Fig. 9). Before it reaches the weir the main channel is 8.72 km long, with a slightly sinuous layout (index of 1.07, according to the Morisawa (1985) classification). The drainage network consists of 583 channel segments reaching 125.8 km in total length. It has five orders according to the Strahler (1964) method, with bifurcation rate values of between 3 and 7.66, and showing an adequate hierarchy that favors the drainage of the area. Its density is 7.47 km/km², indicating a medium texture (Gregory and Walling (1973) classification). These values, together with the elongated shape of the basin and its strong gradient (between 811 and 460 m, 4.2‰), favor a fast flow transmission through the weir during rainy periods. This was probably the why the site was selected for the construction.

The presence of the weir not only caused aggradation upstream of the construction, but also an increase in the stream gradient downstream. At present, the

stream must abruptly descend 2-2.5 m at the weir, favoring an increased incision, which in this section reaches up to 5.5 m and cuts the Miocene substrate of Sariñena Fm lying under the H1 accumulation. At the foot of H1 there is a relic of the H2 terrace, attached to a stone defense wall (wall 1, Figs. 8b, c). This wall must have been built to protect the upper artificial channel from erosion, probably potentiated by the weir construction. This wall was reinforced by constructing a second one wall (wall 2) and filling the room between them with soft material (point 3 Figs. 6a, b; Figs. 8b, c). This fill is visible because some of the stones have fallen. The H3 terrace was sedimented on the second wall. These types of relationships enable us to infer chronological data for this set of human and natural landforms.
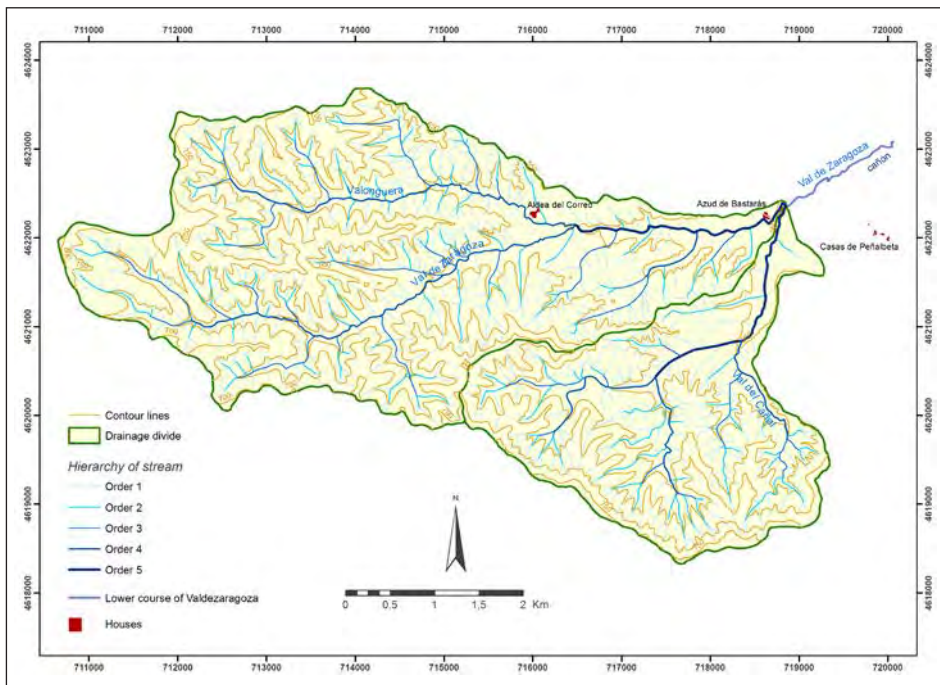

Figure 9. Drainage map of the Val de Zaragoza basin, closed by the Bastarás weir, with the main characteristics of the fluvial network.

At the confluence of the Val de Zaragoza and Val del Cañal streams (Figs. 3, 6), a narrow deposit of level H1t and several outcrops of levels H3 and H2 are conserved in a meander (Figs. 10a, b). On the right margin, there are three stepped units, with the development of an H2s slope deposit connecting the H1t scarp with the top of H2t deposit. H2 is thin and overlaps H1. However, H3t forms an independent accumulation surface (Fig. 10b). This circumstance is repeated on the left margin of the stream, where a long H2s slope begins in the artificial channel levee area and forms a 2.5-m high scarp on the floodplain. However, most of the profile is composed of H1t deposit (2 m of the lower section) (Fig. 10c, point 4 in Figs. 6a, b), and only

the upper 0.5 m belongs to H2. The lower section of H1t is composed of silt and sand layers, with interbedded gravel channels, and three layers with abundant charcoal fragments. The section was dated at 4820-4621 cal yr BP (VZ-04, Table 1).

From its confluence with the Val del Cañal, the Val de Zaragoza stream begins to deepen in the alluvial cone of level H1, excavating a canyon in the Miocene substrate. In a profile at the beginning of the canyon it is possible to observe the original shape of the Val de Zaragoza during the formation of the H1 cone. The channel was NNE-oriented (Fig. 6a, upper left), while the present stream is NE-oriented on the cone margin. There are no accumulations in this area (Fig. 6b).
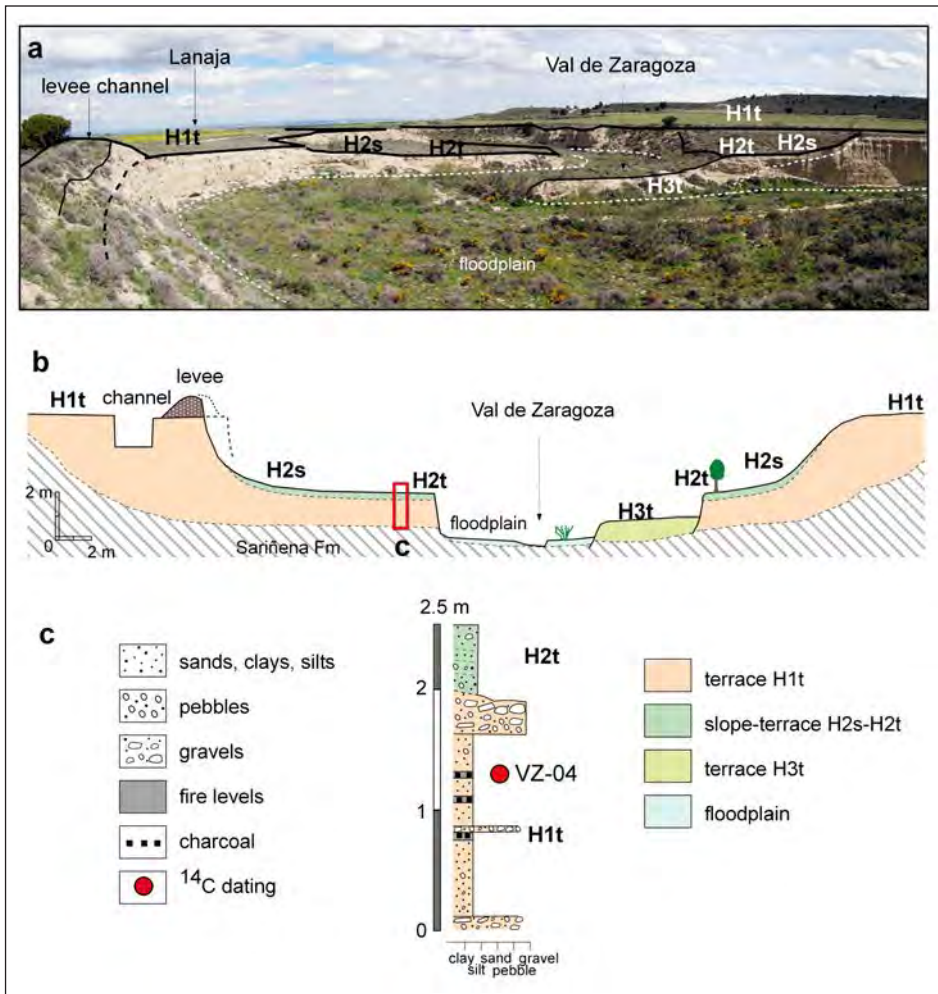

Figure 10. a) and b) transversal cross section of Val de Zaragoza in the meander close to the confluence with Val del Juncal; see the different accumulation levels and the position of the (c) stratigraphic profile.

5. Discussion

The sequence of aggradational/degradational phases observed at the Val de Zaragoza shows an evolutionary process similar to other valleys in the Ebro basin. However, the South-North arrangement of Val de Zaragoza and its trajectory through non-gypsum substrate, makes this valley a very valuable case study. The two main accumulation surfaces are H1 and H2 units, whose geomorphological and chronological characteristics are contextualized within a regional framework to explore their paleoenvironmental meaning, relate them to the global Holocene data, and interpret the regional impacts of human activities.

5.1. *Accumulative stage H1: chronology and main features*

In the center of the Ebro basin (Figs. 1c, 11c, Table 3), the age of the H1 terrace is controversial although it seems its fill is the result of three overlapped aggradation phases. The oldest ages obtained for H1 aggradational stage correspond to Val de Osera (11396-11196 cal yr BP) (Arauzo and Gutiérrez, 1994), and Valsalada (12628-12418 cal yr BP) (Sancho *et al.*, 2007a). In Bardenas Reales de Navarra, in the center west of the basin, Peña Monné *et al.* (2006) and Sancho *et al.* (2007b, 2008) dated the oldest phase at 9380-7950 cal yr BP. This means that for the central part of the Ebro basin the first accumulation phase, hereby called H1A (Fig. 11f), occurred in the Early Holocene. A broader chronological group of dates, yields ages younger than 8200 BP for the H1 deposits (Table 3). This is the case of the Huerva River, where Val de las Lenas was dated to 7154-6437 cal yr BP, Val de la Morera to 6949-6751 cal yr BP, and Cuarte to 4840-4627 cal yr BP (Peña Monné *et al.*, 1993, 1998, 2001, 2004). In addition, Val de la Virgen, El Sisallar, and Alfocea, in the NW area of the Ebro scarp record (Fig.1c), were dated to 8033-7950 cal yr BP, 4965-4821 cal yr BP, and 4956-4709 cal yr BP, respectively. Similarly, Val de Nuez was dated to 5986-5756 cal yr BP and 5469-5318 cal yr BP (Constante *et al.*, 2010, 2011). This set covers the Atlantic and Subboreal periods (Figs. 11a, b), and is culturally represented by the Neolithic and Chalcolithic (Fig. 11g). During those times, the regional climate was better for human occupation, and settlements resulted in thicker sedimentary records than in previous phases. The radiocarbon datings obtained in the lower sections of H1 from Val de Zaragoza belong to this chronological group. Datings are very similar: 4785-4526 cal yr BP at Aldea del Correo, 4821-4628 cal yr BP upstream of the weir, and 4820-4621 cal yr BP downstream (Fig. 11d). This wide initial phase, with variable beginning dates depending on the area, cover just one third of the H1 accumulation (the first 1-3 m of sediments, approximately) (Fig. 11e). This section reflects less human influence and so climate changes were probably the most important factor in its formation during the Early and Middle Holocene, as shown in Fig. 11b by the NGRIP curve (Rasmussen *et al.*, 2007) and Bond events (Bond *et al.*, 1997). However, data is too scarce to establish stronger connections with these environmental fluctuations.
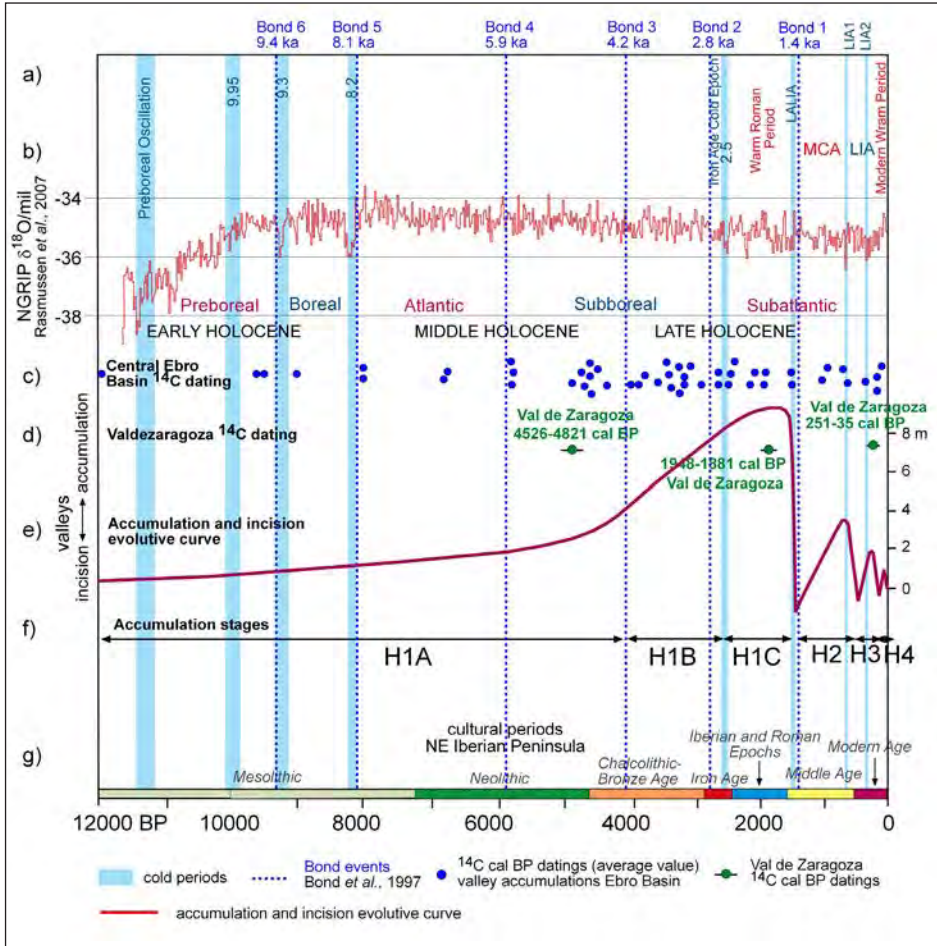
Figure 11. Paleoenvironmental and chronological information of the valleys of the central Ebro basin and the Val de Zaragoza on the Holocene environmental context: a) Chronological framework with the main Holocene climatic stages and Bond events (Bond et al., *1997); b) NGRIP curve (Rasmussen* et al., *2007); c) calibrated radiocarbon datings from various valleys in the area (bibliographic references on the text); d) radiocarbon datings of the Val de Zaragoza; e) evolutionary curve proposed according to sedimentation and incision rates in the Ebro basin (expressed in m approximately); f) Holocene accumulation stages identified; g) cultural periods from the NE of the Iberian Peninsula.*

Table 3. Main Holocene valley fills radiocarbon datings from the central sector of the Ebro Basin.

Sampled valleys and references (*)	Age ¹⁴C BP	Age Cal BP 1s	Age cal BC/AD 1s	Unit	Thickness outcrop (m)	Depth of sampling (m)	Aggradation rate (m/1000 yrs)
Val de la Morera (3) Peña Monné *et al.*, 1998	6015±75	6949-6751	5000-4802 BC	H1A	10.2	9.8	] 1.5
	3260±60	3563-3410	1614-1461 BC	H1B	10.2	6	
	380±60	503-325	1448-1625 AD	H2	2	1.5	
Val de las Lenas (4) Peña Monné *et al.*, 1993	5910±270	7154-6437	5205-4488 BC	H1A	10.3	7	] 0.5
	2470±150	2718-2378	769-429 BC	H1C	10.3	9.1	
	1960±210	2289-1629	340 BC-322 AD	H1C	5	3.7	
Cuarte-Santa Fe (5) Peña Monné *et al.*, 1998	4195±65	4840-4627	2891-2678 BC	H1A	5	4.5	
	3440±150	3891-3495	1942-1546 BC	H1B	5	4.5	
	2420±170	2733-2336	784-387 BC	H1C	5	4	
	500±150	658-331	1292-1620 AD	H2	4.5	1.2	
Valmadrid (6) Calvo and Soriano, 1987; Soriano, 1989	2140±220	2361-1825	412 BC-125 AD	H1C	6	2	
	2000±80	2060-1868	111 BC-83 AD	H1C	6	2	
Val de la Virgen (8) Constante *et al.*, 2010	7185±65	8033-7950	6084-6001 BC	H1A	11.3	6.7	
	3285±60	3566-3456	1617-1507 BC	H1B	8	4.7	] 9
	3075±60	3356-3231	1407-1282 BC	H1B	8	2.7	
	3135±50	3442-3256	1493-1307 BC	H1B	4	3.5	
	2855±50	3059-2885	1110-936 BC	H1B	6	5.2	] 12.2
	2645±50	2840-2738	891-789 BC	H1B	6	3	
El Sisallar (9) Constante *et al.*, 2011	4285±60	4965-4821	3016-2872 BC	H1A	8.3	5.6	] 1.2
	3535±60	3893-3720	1944-1771 BC	H1B	8.3	4.2	
	1570±55	1526-1409	425-541 AD	H1C	8.3	2	
	1495±55	1476-1312	474-639 AD	H1C	8.3	1.8	
Val de Alfocea (10) Constante *et al.*, 2009	4270±55	4956-4709	3007-2760 BC	H1A	8	7.5	] 4
	3610±60	4061-3838	2112-1889 BC	H1B	8	2.7	
Val de Nuez (12) Constante *et al.*, 2010	5140±60	5986-5756	4037-3807 BC	H1A	7.5	3.8	
	4675±60	5469-5319	3520-3370 BC	H1A	6	4	
Villafranca (13) Arauzo and Gutierrez, 1994	3760±70	4237-3991	2288-2042 BC	H1A	6	2.4	
Val de Osera (14) Arauzo and Gutiérrez, 1994	9865±85	11396-11196	9447-9247 BC	H1A	3	3	
	3440±95	3831-3593	1882-1644 BC	H1B	6.3	1.8	
Valsalada (15) Sancho *et al.*, 2007	10550±80	12628-12418	10679-10469 BC	H1A	4	2.6	
	3225±50	3547-3383	1598-1434 BC	H1C	4.7	1.2	
	1640±50	1608-1419	342-531 AD	H2	5	0.5	
Valdezaragoza (1) (2) This paper	4160±30	4821-4628	2872-2679 BC	H1A	8.35	5.35	
	4153±30	4820-4621	2871-2672 BC	H1A	3	2.7	
	4090±29	4785-4526	2836-2571 BC	H1A	2.5	1.4	
	1970±30	1948-1882	2-68 AD	H1C	2.35	1.9	
	100.16±0.36	251-35	1699-1915 AD	H2	4	1.3	

(*) location number Fig. 1c. Data about the thickness of the analysed outcrops, depth of the samples, and aggradational rates of some accumulations are indicated.

The second accumulation period (H1B phase), recorded in the middle units of the H1 terrace fill, was formed in the transition between the Middle and the Late Holocene. From a cultural point of view, it covers the end of the Chalcolithic and the Bronze and Iron Ages, spanning from 4200 to 2500 BP (Fig. 11g). This age correlates with the dates obtained in other *vales* such as (Fig. 11c, Table 3), Val de La Virgen (between 2738 and 3456 cal yr BP), Sisallar (3893-3720 cal yr BP), and Alfocea (4061-3838 cal yr BP) (Constante *et al.*, 2006, 2009, 2010, 2011), Villafranca de Ebro (4237-3991 cal yr BP) and Osera (3831-3593 cal yr BP) (Arauzo and Gutiérrez, 1994) (Ebro scarp) and the areas of Santa Fe (3891-3485 cal yr BP), Val de la Morera (3563-3410 cal yr BP) (Huerva River) (Peña Monné *et al.*, 1998, 2004), and Valsalada (3547-3383 cal yr BP) (Sancho *et al.*, 2007a). Similarly, at Bardenas Reales de Navarra, Sancho *et al.* (2008) dated this phase at 3270-3520 cal yr BP. This group of ages covers the end of the Subboreal period, with one Bond events (4.2) (Fig. 11a). It is also a phase with big cultural changes, like those of the Bronze and Iron Ages (Fig. 11g). During those ages, significant population growth was accompanied by constant technical improvement that led to greater pressure on the landscape and consequently, an increase in the erosion rate and infilling processes of the valleys (Fig. 11e). This period has not been dated at the Val de Zaragoza yet.

The end of H1 accumulation phase (H1C) spans from the end of the Iron Age-Ibero-Roman Epoch (5th century BC) to the Late Roman Epoch (5th century AD). At the Val de Zaragoza this accumulation is well represented with a date of 1970 ± 30 ^{14}C yr BP (1948-1882 cal yr BP) and a large number of ceramic fragments of similar age. The same Roman end of the stage was observed at Valmadrid, SE Zaragoza, by Soriano and Calvo (1987) and Soriano (1989) (2361-1825 and 2060-1868 cal yr BP), at Val de las Lenas (2718-2378 cal yr BP, 2289-1629 cal yr BP), El Sisallar (1526-1409 cal yr BP, 1476-1312 cal yr BP), and Santa Fe (2733-2336 cal yr BP) by Peña Monné *et al.* (1993, 2001, 2004), at Valsalada (1608-1419 cal yr BP) by Sancho *et al.* (2008) (Fig. 11c, Table 3), and in the valley fills around Juslibol castle, in the Ebro scarp by Peña Monné (1996).

These datings are accompanied in the Val de Zaragoza (level B in Fig.7e), as well as in the Val de la Morera and Val de las Lenas, by deposits enriched with charcoals and ashes, and so indicating extensive fires. In addition, these deposits contain a large number of ceramic potsherds and ruins that evidence the strong human pressure on the landscape. In the Huerva Valley and Castillo de Juslibol, H1C is the thickest stage, showing the increasing land degradation while the deposit was forming (Constante and Peña-Monné, 2009; Peña Monné *et al.*, 2014). Climatically, this stage was dominated by the Roman Warm Period (Fig. 11a), also favorable for degradational processes. In Val de Zaragoza, unit C of the Bastarás weir sector (Figs. 7d, e) reaches more than 1.5 m of fine sediments deposited since the 1st century AD, but no further chronological data of the final layer is available. However, in the Huerva Valley (Val de las Lenas, Cuarte, and Val de la Morera) and Mediana de Aragón (Ginel River) (Burillo *et al.*, 1985), the fills cover the Roman *villae* of later times (3rd and 4th centuries AD) (Peña Monné *et al.*, 2004).

The subdivision of H1 aggradational phases is not necessarily similar across the entire region since it is strongly dependent on the local human impact. The erosive

processes triggered by intense forest exploitation, fires, and agriculture had a major impact during the Bronze Age in some sectors (such as the Ebro scarp) (Constante *et al.*, 2010), while in other places, such as the Huerva valley, the most significant anthropogenic activity correspond to Roman times (Peña Monné *et al.*, 2004). The situation is similar at the Val de Zaragoza.

In the Ebro depression, after the formation of the Late Roman deposits (by the end of H1C) a remarkable dynamic change occurred after the 4th century AD and before Visigothic times, when incision processes on H1 deposits became dominant (Peña Monné *et al.*, 2004). This is supported by the existence of graves from the 7th century over those fills in the area of Cuarte (Gutiérrez Elorza and Peña Monné, 1998), which indicates that it had already become a non-functional level. According to its chronology (Fig. 11a), the incision phase may have been related to the environmental change caused by the cold and wet 1.4 Bond event (Bond *et al.*, 1997) during the LALIA (Late Antique Little Ice Age, 530-660 AD) (Büntgen *et al.*, 2016) or Dark Ages Cold Period (DCAP) (Helama *et al.*, 2017).

5.2. *Accumulative stages H2 and H3: Chronology and characteristics*

In the inner part of the present channel terrace surfaces H2 and H3 are inset on H1 terrace fill and separated by an intermediate incision phase (Fig. 11e). These recent aggradational and erosional stages have a less abundant record in the Ebro basin; this is because most of the *vales* are still filled by H1 deposits and only the lowest reaches closer to the main rivers are affected by an incision wave controlled by piping processes. Thus, H2 and H3 are often thin (1-3 m) and restricted to lower reaches. In Val de Zaragoza, Aldea del Correo, and in the sector of the weir of Bastarás, these stages are represented by slope and fluvial deposits inset and unconformably overlaying H1 deposits (Figs. 7a, e, 10b, c).

Their datings are scarce and problematic due to the impossibility of calibration. Traditionally, the H2 stage was considered "post-Medieval" because it had Medieval ceramics in several valleys of the Central Ebro Basin, and H3 stage was associated with part of the Little Ice Age (Peña Monné *et al*., 2004 and Pérez-Lambán *et al.*, 2014). At present, it is possible to classify the datings into two groups that reflect the real chronology.

In the Val de la Morera (Huerva valley) a level was dated to 503-325 cal yr BP (Peña Monné *et al.*, 2004) and in Santa Fe to 658-331 cal yr BP (Peña Monné *et al.*, 1998). These datings are framed within H2 accumulations (LIA 1, Figs. 11a, b, c, Table 3), approximately correlated with the Spörer Minimum (1460 and 1550 AD), and characterized by wet and cold conditions in the Southern Pyrenees (Morellón *et al.*, 2012). Moreover, the H3 stage (LIA 2, Fig. 11) was dated between 360 ± 101 cal yr BP and 216 ± 89 cal yr BP in the Bardenas Reales de Navarra (Sancho *et al.*, 2007b). The only date (251-35 cal yr BP) obtained at Val de Zaragoza from a sequence of charcoal layers, near Aldea del Correo, also corresponds to stage H3 (Figs. 5c, d). The important contribution of charcoal and ashes incorporated to the H3 fill supports an increase in the erosion rates of the upper slopes during this time in response to an intense human impact on the basin landscape from the end of the 18th century to the first half of the 19th

century with the aim of supplying charcoal to the growing city of Zaragoza. From the climatic point of view, the date of H3 terrace is coincident with the end of the LIA (Figs. 11a, e, f), probably related to the Dalton Minimum (1790-1830), with cold winters and increased snow in the south of the Pyrenees (Saz, 2007; Morellón *et al.*, 2012) especially in high north-oriented areas, such as the Val de Zaragoza basin. The period was also characterized by events of strong precipitations, floods of the main rivers and also of the secondary courses, such as the *vales* (Peña Monné *et al.*, 2004).

The increase in water availability must have inspired the owners of the Bastarás property to build a weir for irrigation in the Val de Zaragoza. The exact construction date is unknown because there are no documents. According to some references obtained from the owners of the land, the weir functioned until at least the middle of the 19th century. An important datum is that the walls protecting the channel downstream of the weir are on H2 terrace deposits. Therefore, they were constructed after H2 sedimentation but also after its incision. Besides, level H3 is laterally supported by these walls, so it fits well chronologically into the calculated time of construction.

The information obtained from the Holocene accumulations from Val de Zaragoza allowed getting an almost complete evolutionary Holocene sequence. However, it was not possible to establish the aggradation rates of the different units. This is because there are no datings at different depths on each outcrop. Moreover, according to the characteristics of the studied profiles, they values would not be accurate due to the inner erosive discordances observed. In the table 3 the thickness of the outcrops and the depth of the samples were introduced for all cases from the Ebro Basin. Only in the case of Val de la Morera, Val de las Lenas, Val de la Virgen, El Sisallar, and Val de Alfocea was possible to establish partial accumulation rates. They range between 0.5 and 12.2 m/1000 yrs. If we have into consideration that in some cases (Val de las Lenas, la Morera, and de la Virgen) the upper layers could be dated with Roman archaeological materials from 4th to 5th centuries AD (Peña Monné *et al.*, 1993, 1998, 2001, 2004), the accumulation rates would be between 2 and 3 m/1000 yrs for the unit H1, with a maximum in the H1C unit. This data was taken as the mean value for the graph represented in Fig. 11e although it only has a general indicative value.

6. Conclusions

The Val de Zaragoza is a small valley that well represents the hydrological and geomorphological functioning of the fluvial courses in the central sector of the Ebro basin during the Holocene. The cartography and study of several stratigraphic profiles of the valley and its tributaries made it possible to identify an extended and thick H1 accumulation, as well as two nested fluvial terraces forming H2 and H3 accumulations, separated by incision phases. The radiocarbon datings and archaeological remains from two phases enabled establishing correlations with other similar valleys in the Ebro basin.

The relationship of the Val de Zaragoza with the data from different nearby areas enabled to establish a regional evolutionary sequence composed of stages of accumulation and degradation. The first stage (H1) stands out, spanning from the Early Holocene to the

Roman Epoch. It was possible to differentiate three aggradational phases: H1A (13800-4200 BP), H1B (4200-2500 BP), and H1C (2500-1500 BP). The morphosedimentary and chronological description of the profiles located in Aldea del Correo and the Bastarás weir only yielded data about phases A and C. Other data from valleys in the central Ebro basin shows an increase in the sedimentation rate of the basin between the oldest dates (from the Chalcolithic-Bronze Age) until a maximum with the highest values during the Iberian and Roman periods, when human pressure on the landscape was greater.

Accumulation stages H2 and H3 are restricted to the inner part of the incisions dated after the Roman Epoch and generated on H1 deposits. The scarce data available on the central sector of the Ebro depression, together with the radiocarbon dating obtained in Val de Zaragoza, enable us to locate the formation of H2 in the first phase of the LIA (*ca.* 16th century) and H3 to a second climatic phase of the same period (the end of the 19th and beginning of the 20th centuries), both associated with climatic causes. Moreover, the presence in Val de Zaragoza of several layers with charcoal in this second phase is probably related to charcoal exploitation.

The construction of the Bastarás weir and the artificial channel network is a good testimony of the climatic influence of the LIA. The increase in water availability made it possible to manage water for irrigation and today this land is a rainfed area. The stone fences that were also needed at that time enabled us to increase our chronological knowledge of the evolution of H2 and H3 stages, and infer that water flow was greater than at present.

The geoarchaeological approach to the study of the Val de Zaragoza in the evolutionary framework of the central sector of the Ebro basin is shown as a key tool for gaining an understanding of current landscapes establishing chronological milestones and defining the role of man in triggering many of the key geomorphological processes.

Acknowledgements

References

Alonso-Zarza, A.M., Armenteros, I., Braga, J.C., Muñoz, A., Pujalte, V., Ramos, E. 2002. Tertiary. In: W. Gibbons, T. Moreno (Eds.), *The Geology of Spain*. The Geological Society of London, pp. 293-324.

Arauzo, T., Gutiérrez, M. 1994. Evolución de los valles de fondo plano del centro de la Depresión del Ebro. In: J. Arnáez, J.M. García-Ruiz, A. Gómez-Villar (Eds.), *Geomorfología en España. III Reunión Nacional de Geomorfología*, Logroño, pp. 277-290.

Bintliff, J. 2002. Time, process and catastrophism in the study of Mediterranean alluvial history: a review. *World Archaeology* 33, 417-435. https://doi.org/10.1080/00438240120107459.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., de Menocal, P. Priore, P., Cullen, H., Hajdas, I., Bonani, G. 1997. A pervasive millennial-scale cycle in north Atlantic Holocene and glacial climates. *Science* 278, 1257-1266. https://doi.org/10.1126/science.278.5341.1257.

Burillo, F., Gutiérrez, M., Peña Monné, J.L. 1985. Las acumulaciones holocenas y su datación arqueológica en Mediana de Aragón (Zaragoza*). Cuadernos de Investigación Geográfica* 11, 193-207. https://doi.org/10.18172/cig.955.

Brückner, H. 1986. Man's impact on the evolution of the physical environment in the Mediterranean region in historical times. *GeoJournal* 13 (1), 7-17. https://doi.org/10.1007/BF00190684.

Büntgen, U., Myglan, V.S., Ljungqvist, F.C., McCormick, M., Di Cosmo, N., Sigl, M. Jungclaus, J., Wagner, S., Krusic, P.J., Esper, J., Kaplan, J.O., De Vaan, M.A.C., Luterbacher, J., Wacker, L., Tegel, W., Kirdyanov, A.V. 2016. Cooling and societal change during the Late Antique Little Ice Age from 536 to around 660 AD. *Nature Geoscience* 9, 231-236. https://doi.org/10.1038/ngeo2652.

Butzer, K.W. 2005. Environmental history in the Mediterranean world: Cross-disciplinary investigation of cause-and-effect for degradation and soil erosion. *Journal of Archaeological Science* 32, 1773-1800. https://doi.org/10.1016/j.jas.2005.06.001.

Constante, A., Dossche, R., Peña Monné, J.L., Sancho, C., de Dapper, M. 2006. Dinámica morfosedimentaria holocena en laderas y valles del escarpe de Alfocea-Juslibol (sector central de la Depresión del Ebro). In: A. Pérez Alberti, J. López Bedoya (Eds.), *Geomorfología y territorio*. Santiago de Compostela, pp. 979-992.

Constante, A., Dossche, R., Peña-Monné, J.L., Sancho, C., de Dapper, M. 2009. Holocene evolution and geoarchaeology in the Ebro valley around Zaragoza (Northern Spain). In: M. De Dapper, F. Vermeulen, S. Deprez, D. Taelman (Eds.), *Ol´man river Geo-archaeological aspects of rivers and river plains*. Academia Press, Ghent, pp. 241-256.

Constante, A., Peña-Monné, J.L. 2009. Human-induced erosion and sedimentation during the Holocene in the central Ebro depresión, Spain. In: A. Romero, F. Belmonte, F. Alonso, F. López-Bermúdez (Eds.), *Advances in studies on desertification*. Universidad de Murcia, pp. 207-210.

Constante, A., Peña Monné, J.L., Muñoz, A. 2010. Alluvial geoarchaeology of an ephemeral stream: Implications for Holocene landscape change in the Central part of the Ebro Depression, Northeast Spain. *Geoarchaeology* 25, 475-496. https://doi.org/10.1002/gea.20314.

Constante, A., Peña Monné, J.L., Muñoz, A., Picazo, J. 2011.Climate and anthropogenic factors affecting alluvial fan development during the Late Holocene in the Central Ebro valley, Northeast Spain. *The Holocene* 21, 275-286. https://doi.org/10.1177/0959683610378873.

Costa, J.M., Ramírez Merino, J.I., Salazar, A. 1998. *Mapa Geológico de España escala 1:5000. Hoja 356 Lanaja.* IGME, Madrid.

Domínguez Arranz, M.A., Magallón, M.A., Casado López, M.P. 1984. *Carta Arqueológica de España: Huesca*. Diputación Provincial, Huesca.

García Esteban, L., Guindeo Casasús, A., Peraza Oramas, C., de Palacios, P. 2003. *La madera y su anatomía. Anomalías y defectos, estructura microscópica de coníferas y frondosas, identificación de maderas, descripción de especies y pared celular.* Mundi-Prensa, Madrid.

Giral Royo, F. 2004. Introducción al poblamiento de época romana en Los Monegros. *Revista d'Arqueología de Ponent* 14, 223-236.

Gregory, K.J., Walling, D.E. 1973. *Drainage basin. Form and process: a geomorphological approach.* London. Edward Arnold.

Gutiérrez Elorza, M., Peña Monné, J.L. 1998. Geomorphology and Late Holocene Climatic Change in Northeastern Spain. *Geomorphology* 23, 205-217. https://doi.org/10.1016/S0169-555X(98)00004-X.

Helama, S., Jones, P.D., Briffa, K.R. 2017. Dark Ages Cold Period: A literature review and directions for future research. *The Holocene* 1-7. https://doi.org/10.1177/0959683617693898.

Lasaosa, R. 1997. *Lanaja. La vida en un pueblo de Monegros antes de los regadíos*. Edición La Val de Onsera, Huesca. Spain.

Mattingly, H., Sydenham, E.A. 1968. *Roman Imperial Coinage*, vol. 2*, Vespasian to Hadrian.* Spink & Son, London.

Morellón, M., Pérez-Sanz, A., Corella, J.P., Büntgen, U., Catalán, J., González-Sampériz, P., González-Trueba, J.J., López-Saéz, J.A., Moreno, A., Pla-Rabes, S., Saz-Sánchez, M.A., Scussolini, P., Serrano, E., Steinhilber, F., Stefanova, V., Vegas-Villarubia, T., Valero-Garcés, B. 2012. A multi-proxy perspective on millennium-long climate variability in the Southern Pyrenees. *Climate of the Past* 8, 683-700. https://doi.org/10.5194/cp-8-683-2012.

Morisawa, M. 1985. *Rivers. Form and process*. In: K.M. Clayton (Ed.), *Geomorphology texts*. University of East Anglia.London and New York.

Peña Monné, J.L. 1996. Los valles holocenos del escarpe de yesos de Juslibol (sector central de la Depresión del Ebro). Aspectos geomorfológicos y geoarqueológicos. *Arqueología Espacial* 15, 83-102.

Peña Monné, J.L. 1997. *Cartografía geomorfológica básica y aplicada*. Geoforma Ediciones, Logroño, 227 pp.

Peña Monné, J.L., Chueca, J., Julián, A., Echeverría, M.T. 1996. Reconstrucciones paleoambientales en el sector central de la Depresión del Ebro a partir de rellenos de valle y conos aluviales. In: A. Pérez-Alberti, P. Martini, W. Chesworth, A. Martínez-Cortizas (Eds*.), Dinámica y evolución de medios cuaternarios*. Xunta de Galicia, Sanbtiago de Compostela, pp. 291-307.

Peña Monné, J.L., Echeverría, M.T., Chueca J., Julián, A. 2001. Processus géomorphologiques d´accumulation et incision pendant l´Antiquité Classique et ses rapport avec l´activité humaine et les changements climatiques holocènes dans la vallée de la Huerva (Bassin de l´Ebre, Espagne). In: F. Vermeulen, M. de Dapper (Eds.), *Geoarchaeology of the Landscapes of Classical Antiquity*. Leuven, Belgium, pp. 151-159.

Peña Monné, J.L., Echeverría, M.T., Petit-Maire, N., Lafont, R. 1993. Cronología e interpretación de las acumulaciones holocenas de la Val de las Lenas (Depresión del Ebro, Zaragoza*). Geographicalia* 30, 321-332.

Peña Monné, J.L., Julián, A., Chueca, J., Echeverría, M.T. 1998. Los estudios geoarqueológicos en la reconstrucción del paisaje. Su aplicación en el valle bajo del río Huerva*. Arqueología Espacial* 19-20, 169-183.

Peña Monné, J.L., Julián, A., Chueca, J., Echeverría, M.T., Ángeles, G. 2004. Etapas de evolución holocena en el valle del río Huerva: Geomorfología y Geoarqueología. In: J.L. Peña Monné, L.A. Longares, M. Sánchez-Fabre (Eds.), *Geografía Física de Aragón. Aspectos generales y temáticos.* Universidad de Zaragoza e Institución Fernando el Católico, pp. 289-302.

Peña Monné, J.L., Rubio, V., González, J.R. 2005. Aplicación de modelos geomorfológicos evolutivos al estudio de yacimientos arqueológicos en medios semiáridos (Depresión del Ebro, España). *X Coloquio Ibérico de Geografía. A Geografia ibérica no cotexto europeo* (15 p.) Évora, CD.

Peña-Monné, J.L., Sampietro-Vattuone, M.M. 2014. Geoarchaeological and paleoenvironmental reconstruction through evolutionary models: Dryland applications. *European Geologist Magazine* 38, 40-44.

Peña Monné, J.L., Sancho, C., Muñoz, A., Benito, G., Longares, L.A., McDonald, E., Rhodes, E. 2006. Morfoestratigrafía del registro aluvial Pleistoceno superior-Holoceno del Barranco

Grande (Bardenas Reales): aproximación a su significado paleoambiental. In: A. Pérez-Alberti, J. López-Bedoya (Eds.), *Geomorfología y Territorio*. Universidad de Santiago de Compostela, pp. 655-668.

Peña Monné, J.L., Sancho, C., Muñoz, A., Constante, A. 2014. Clima y hombre en la evolución de las vales del sector central de la Depresión del Ebro durante el Holoceno superior. In: J. Arnáez, P. González-Sampériz, T. Lasanta, B.L. Valero (Eds.), *Geoecología, cambio ambiental y paisaje: Homenaje al profesor José María García Ruiz*, Inst. Pirenaico de Ecología, Universidad de La Rioja, 91-102.

Pérez-Lambám, F., Peña-Monné, J.L., Fanlo, J., Picazo, J.V., Badia, D., Rubio, V., García-Jiménez, R., Sampietro-Vattuone, M.M. 2014. Paleoenvironmental and geoarchaeological reconstruction from late Holocene slope records (Lower Huerva Valley, Ebro Basin, NE Spain). *Quaternary Research* 8, 1-14. https://doi.org/10.1016/j.yqres.2013.10.011.

Pope, K.O., van Andel, T.H. 1984. Late Quaternary alluviation and soil formation in the southern Argolid: its history, causes and archaeological implications. *Journal of Archaeological Science* 11, 281-306. https://doi.org/10.1016/0305-4403(84)90012-8.

Quirantes, J. 1978. *Estudio sedimentológico del Terciario continental de los Monegros*. Institución Fernando el Católico, Zaragoza.

Rasmussen, S.O., Vinther, B.M., Clausen, H.B., Andersen, K.K. 2007. Early Holocene climate oscillations recorded in three Greenland ice cores. *Quaternary Science Reviews* 26, 1907-1914. https://doi.org/10.1016/j.quascirev.2007.06.015.

Riba, O., Reguant, S., Villena, J. 1983. Ensayo de síntesis estratigráfica y evolutiva de la cuenca terciaria del Ebro. In*: Libro Jubilar J.M. Ríos*, Instituto Geológico Minero de España, Madrid, pp. 131-159.

Salvany, J.M., García-Veigas, J., Ortí, F. 2007. Glauberite-halite association of the Zaragoza Gypsum Formation (Lower Miocene, Ebro Basin, NE Spain). *Sedimentology* 54**,** 443-467. https://doi.org/10.1111/j.1365-3091.2006.00844.x.

Sancho, C., Muñoz, A., Peña Monné, J.L., González, P. 2007a. Evolución morfosedimentaria del sistema aluvial de Valsalada (Leciñena, Los Monegros) durante el Pleistoceno superior-Holoceno: aproximación paleoambiental. *Geogaceta* 41, 199-202.

Sancho, C., Benito, G., Peña Monné, J.L., Longares, L.A., McDonald, E., Rhodes, E., Saz, M.A. 2007b. Actividad aluvial durante la Pequeña Edad del Hielo en Bardenas Reales de Navarra. *Geogaceta* 42, 111-114.

Sancho, C., Peña Monné, J.L., Muñoz, A., Benito, G. McDonald, E., Rhodes, E., Longares, L.A. 2008. Holocene alluvial morphopedosedimentary record and environmental changes in the Bardenas Reales Natural Park (NE Spain). *Catena* 73, 225-238. https://doi.org/10.1016/j.catena.2007.09.011.

Saz, M.A. 2007. Evolución de las temperaturas medias de la estación cálida (abril-septiembre) en la mitad norte de España durante la Pequeña Edad del Hielo (siglos XVI al XIX). *Geographicalia* 52, 143-163.

Schweingruber, F.H. 1990. *Anatomie Europäischer Hölzer*. Haupt, Bern und Stuttgart.

Soriano, M.A. 1989. Infilled valleys in the Central Ebro Basin (Spain). *Catena* 16, 357-367. https://doi.org/10.1016/0341-8162(89)90020-9.

Soriano, M.A., Calvo, J.M. 1987. Características, datación y evolución de los valles de fondo plano de las inmediaciones de Zaragoza. *Cuaternario y Geomorfología* 1, 283-293.

Strahler, A.N. 1964. *Quantitative geomorphology of drainage basins and channel networks*. Section 4-II of Handbooks of Applied Hydrology, McGraw-Hill Book Co., New York.

Vernet, J.L. 1973. Étude sur l'histoire de la végétation du Sud-Est de la France au Quaternaire d'après l'étude des charbons de bois principalement. *Paléobiologie Continentale* 4, 1-90.

Vernet, J.L., Ogereau, P., Figueiral, I., Machado Yanes, C., Uzquiano, P. 2001. *Guide d'identification des charbons de bois préhistoriques et récents. Sud-Ouest de l'Europe: France, Péninsule ibérique et îles Canaries*. CNRS, París.

Van Zuidam, R.A. 1975. Geomorphology and Archaeology. Evidences of interrelation at historical sites in the Zaragoza region, Spain. *Zeitscrift fur Geomorphologie* 19, 319-328.

Vita-Finzi, C. 1969. *The Mediterranean valleys. Geological changes in historical times*. Cambridge University Press, Cambridge, 140 pp.