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Dating the Earliest Pleistocene alluvial terrace of the Alcanadre River (Ebro Basin, NE Spain): Insights into the landscape evolution and involved processes

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ABSTRACT

This work presents the results of a multi-approach study of the extensive highest terrace (Qt1) of the Alcanadre River system (Ebro Basin, Spain). The timing of the earliest morphosedimentary fluvial archives in the Ebro Basin (NE Spain) under exorheic conditions is provided from ESR dating techniques applied to optically bleached quartz grains and complemented by palaeomagnetic data and morphopedosedimentary features. A mean ESR age estimate of 1276 ± 104 ka based on the Ti-centre provides the oldest numerical age obtained for a Quaternary terrace in the Iberian Peninsula. The polarity determined by palaeomagnetic analysis is normal, although it must be contained within the Matuyama reversed period. Therefore, Cobb Mt is the more suitable chron, although Jaramillo cannot be fully ruled out. This age is consistent with the last stretch of the Matuyama reversed Chron deduced from palaeomagnetism. Relevant consequences concerning the palaeogeographical setting, palaeoclimatic context and fluvial incision rates are discussed to elucidate the landscape evolution of NE Iberia.

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1. Introduction

The Ebro Basin is a large drainage depression in the NE Iberian Peninsula. Intensive Quaternary research began in the 1970s, and a good understanding (mapping, geomorphological features and forming processes) of the main morphosedimentary units outcropping in the Central sector of the Ebro Basin is currently available (Gutiérrez and Peña, 1994). The large sequence of Pleistocene staircase terraces related to the drainage network guided by the Ebro River is remarkable. Nevertheless, the timing of terrace

formation and landscape evolution of the Ebro Basin suffers from an important lack of numerical ages (Santisteban and Schulte, 2007). Recently, a significant effort has been made to date staircase terrace sequences in some of the main tributaries of the Ebro River based on luminescence (Fuller et al., 1998; Lewis et al., 2009; Benito et al., 2010; Calle et al., 2013), terrestrial cosmogenic nuclides (Stange et al., 2013) and palaeomagnetism (Sancho et al., 2007; Calle et al., 2013; Gil et al., 2013). However, the chronological database currently available refers mainly to fluvial terraces developed over the Middle and Late Pleistocene, whereas no numerical ages have been reported so far for the Early Pleistocene terraces in the Ebro Basin.

That framework is actually quite similar to other studied basins in Spain (Silva et al., 2013), for which only one single ESR age of 1.140 ± 0.13 Ma is documented in the Arlanzón River valley (Duero Basin) (Moreno et al., 2012). It is also noteworthy, the ESR age of

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0.903 ± 0.058 Ma provided by Rosina et al. (2014) for the earliest fluvial terrace of the Lower Tagus River in Portugal. Palaeomagnetic data from Early Pleistocene terraces are also scarce, highlighting the studies by Pérez-González et al. (2013) in the High Tagus River valley, Benito-Calvo et al. (2008) in the Arlanzón River valley (Duero Basin), Baena and Díaz del Olmo (1994) in the Guadalquivir River valley and Gil et al. (2013) in the Ebro River valley. In addition, Roquero et al. (2014) summarize the available soil data as well as numerical ages from terraces in the Tagus River valley, and they establish several height-age transfer polynomial functions based on soil development indices. As a consequence, the calculated standard ages for the oldest terraces range between 1385 ka (terrace at +84 m above present channel) and 3098 ka (terrace at +130 m above present channel).

Terrace sequences recording Quaternary landscape evolution and their forcing mechanisms have recently been a matter of debate (e.g., Westaway et al., 2009; Vandenberghe et al., 2010; Stokes et al., 2012), underlining the substantial interest in these fluvial archives. In this paper, we present the results of a multi-approach study focused on the oldest terrace level of the Alcanadre River (Qt1 hereafter), a Pyrenean tributary of the Ebro River, in the north-central sector of the Ebro Basin (Fig. 1). A combination of mapping, morphostratigraphy, Electron Spin Resonance (ESR)

dating and palaeomagnetism have been used to characterize and date these deposits, which are of major interest because they are evidence of the earliest fluvial activity in the Ebro Basin under exorheic conditions. Based on these results, several new insights into the Early Pleistocene evolution of the Ebro Basin will be discussed in terms of palaeogeography, palaeoclimate and fluvial incision.

2. Study area

The Ebro Basin was formed during the Palaeogene as a consequence of flexural subsidence related to the growth of surrounding mountain chains, particularly the Pyrenees. During the Oligocene and Miocene, the basin was filled with alluvial, fluvial and lacustrine sediments under conditions of continental internal drainage (Muñoz, 2002). This sedimentary regime persisted until the end of the late Miocene (between 12.5 and 8.5 Ma) when the internal drainage system of the Ebro basin opened to the Mediterranean Sea (García-Castellanos et al., 2003). The lowering of the Mediterranean Sea level and subsequent headward erosion of coastal drainages resulted in the capture of the internal lake system and the onset of the denudation of the Tertiary sedimentary infilling guided by the network of the Ebro River.

Fig. 1. Location of the Alcanadre River watershed in the Ebro Basin (NE Spain).

The Alcanadre River integrates this last network. It is a tributary of the Cinca River which in turn flows into the Ebro River (North-eastern Spain) (Fig. 1). Its headwaters are located in the External Ranges of the Pyrenees and it flows with a meridian trend across the Ebro southern foreland basin (Fig. 1). The Alcanadre River developed an extensive Quaternary staircase terrace system made of nine strath or cut-in-bedrock terraces sequentially named Qt1 (highest) to Qt9 (lowest) (Calle et al., 2013). The terrace sequence of the Alcanadre River is especially well developed in the Sariñena depression located at the lower reach of the valley. It has been mapped and described for a long time (Bomer, 1979; Alberto et al., 1983; Rodríguez, 1983; Sancho, 1988). In particular, the Qt1 terrace has a special relevance in the local landscape because of its extensive outcrop as well as its culminant altitudinal position (Figs. 2 and 3a), developing impressive mesas. This terrace's excellent preservation is coupled with the endurance of highly cemented fluvial sediments (Fig. 3b) by pedogenic processes (Sancho and Meléndez, 1992).

3. Methods

Mapping of the Qt1 terrace of the Alcanadre River utilized aerial photographs (1:30,000 in scale) and was subsequently checked during intensive field work sessions. In addition, deposits were described (fluvial facies and soil horizons) and sampled for ESR dating and palaeomagnetic studies at several outcrops. The altitude of the Qt1 above the sea level (asl) and above the active Alcanadre channel was obtained from both the digital elevation model MDT05/MDT05-LIDAR supplied by the Centro Nacional de Información Geográfica (CNIG) and differential GPS measurements.

3.1. ESR dating of optically bleached quartz grains extracted from sediment

Similarly to Optically Stimulated Luminescence (OSL) dating, the ESR dating method applied to optically bleached quartz grains is based on the study of light-sensitive signals. Consequently, the event dated by these methods is the ~~time that the sediment was been last exposed to sunlight~~. Several types of paramagnetic centres present in quartz have a light-sensitive ESR signal that may potentially be used for dating purposes, such as the Germanium (Ge), Titanium (Ti) and Aluminium (Al) centres. Each of them shows specific characteristics in terms of radiation sensitivity, thermal sensibility or optical bleaching kinetics (Toyoda, 2015). ESR dating applied to quartz grains has been found to be especially useful in a fluvial context, in particular for dating deposits that are beyond the limits of the OSL dating method (e.g., Voinchet et al., 2010; Cordier et al., 2012).

Two sediment samples (ALC1201 and ALC1202) were collected from the Qt1 terrace deposits in the central stretch of the stratigraphic section outcropping in a gravel pit (746694 E 4644299 N, UTM coordinates 30T zone, ETRS89 datum) near Lagunarrotta village (Fig. 2). ALC1201 (Fig. 3c) and ALC1202 were taken from two different outcrops and are vertically separated by approximately 10 m, with ALC1201 being located close to the top of the local sequence and ALC1202 being at the bottom. Sampling was performed by inserting thick PVC tubes into the outcrops to avoid any exposure to sunlight and was intentionally focused on lenses of fine to medium sands surrounded by coarser deposits (Fig. 3c). In situ measurements of the natural radioactivity in the sediment were performed at the exact same location as that of the ESR samples, to obtain the most accurate estimation possible of the gamma dose rate, given the heterogeneity of the sedimentary environment (e.g., Fig. 3c). Additional sediment samples were collected on site for further laboratory analysis.

The ESR dating study was carried out in accordance with the multiple centre (MC) approach first proposed by Toyoda et al. (2000), which is based on the combined measurements of two different paramagnetic centres (namely Al and Ti) in a given sample. ESR dose reconstruction was performed via a Multiple Aliquot Additive (MAA) dose method, i.e., the routine procedure in ESR dating of sedimentary quartz. Complete details about sample preparation and irradiation, ESR measurements and experimental setup may be found in Duval et al. (2015).

Total dose rate calculations were derived from in situ and laboratory analysis: alpha and beta dose rates were derived from the radioelement contents obtained by ICP-OES/MS analysis (Intertek Genalysis, Perth), whereas in situ measurements performed with a 1.5*1.5 inch NaI(Tl) probe coupled with a Canberra Inspector1000 multichannel analyser were used to obtain the gamma dose rate values. Cosmic dose rates were calculated with the formulae from Prescott and Hutton (1994) and corrected according to the altitude, depth and latitude. ESR age calculations were performed with water content values of 18 $\pm$ 5% and 20 $\pm$ 5%. A quite large associated error of 5% (1 σ) was assumed to encompass any possible long and short term variations of the water content over time. ESR ages were calculated with a non-commercial SCILAB program. Full details about dose rate evaluation and age calculation are given in Duval et al. (2015).

3.2. Palaeomagnetic study

Palaeomagnetic sampling was focused on two lutitic layers from two different locations (Qt1.1 and Qt1.2) (Fig. 2). We used standard plastic boxes but also soft sediment extraction devices and an electric drill refrigerated with water, depending upon the degree of consolidation of the lutites. After orienting the samples in the field, sodium silicate solution and aluminium cement were used to consolidate the samples in the laboratory (Pueyo et al., 2006).

The first sampling site (Qt1.1) is located in the quarry to the SW of Lagunarrotta (same site as that of the ESR sampling). The total thickness of the deposits at this site was estimated to be ~11 m. Several sediment samples were taken from a 5–7 cm thick and well-laminated clayish level (Fig. 3d) located 2.1 m above the strath surface and approximately 9 m below the surface of the terrace. The second outcrop (Qt1.2) is located next to the road that leaves El Tormillo to the North (747232 E 4639317 N, UTM coordinates 30T zone, ETRS89 datum). The total thickness of the deposits is approximately 7 m, and several samples were collected from a 40–50 cm thick lutitic layer at 3 m from the strath surface.

Palaeomagnetic vectors were determined after thermal (TH) and alternating field (AF) stepwise demagnetizations in the Palaeomagnetic Laboratory of the University of Burgos (Spain) using a 2G cryogenic magnetometer equipped with AF coils and a TD48 (ASC) furnace. To calculate the characteristic components at the sample level, the Remasoft software (Chadima and Hroudá, 2006), based on principal component analyses (PCA) by Kirschvink (1980), was used. The Fisher distribution (Fisher, 1953) was used to calculate the average for every site with the same software.

4. Results

4.1. Geomorphological and sedimentary features

Remnants of the highest, and consequently oldest, terrace of the Alcanadre River produce large mesas in the local landscape and currently constitute the water divide between the Cinca and Alcanadre drainage networks (Fig. 3e). A wide aggradational sheet and an extensive outcrop of 20 km in length (NNE–SSW) and 10 km in width, with an unrooted broad fan shape, is preserved (Fig. 2).

Fig. 2. Geomorphological mapping of the Qt1 terrace of the Alcanadre River. The palaeofluvial braided network has been drawn from the interpretation of aerial photographs. Sampling (ESR and palaeomagnetism) sites are also indicated.

Unrooting is related to the increased proximal erosion close the upland source area. Proximal dissection is very common on alluviated piedmonts and it occurs in response to complex changes in the drainage system affecting the erosional-depositional balance in that area (Dohrenwend, 1994).

The highest point of the terrace is located in the proximal sector (Berbegal village, Fig. 2), with an elevation of 520 m asl, which is equivalent to a height of 200 m above the active channel. In comparison, the altitude of Qt1 is 410 m asl and 160 m above the active

channel in the distal sector (near Castelflorite, Fig. 2). The mean steepness of the profile is 5.1‰ (Fig. 3e), and the steepness increases towards the headwaters.

Outcropping deposits linked to the strath terrace are quite homogeneous, and have an average thickness of 6 m and can reach as thick as 11 m. The sediment is mainly composed of massive and cross-stratified gravels arranged in decimetric to metric tabular sets limited by erosive surfaces (Fig. 3b). Usually, there is no significant vertical evolution within the sets or even within the complete

Fig. 3. Some features of the Qt1 terrace. Importance of Qt1 in the local landscape (a). Sedimentological and pedogenic features of Qt1 in the gravel peat opened near Lagunarrota (b). Sand lens sampled (ALC1202) for ESR dating (c). Level of lutite near the strath of the terrace sampled for palaeomagnetic analysis (Qt1.1) (d). Profile of the preserved stretch of the Qt1 terrace showing the longitudinal gradient and cross section showing the interfluvial position related to the Alcanadre and Cinca rivers (e).

gravel body. Locally, sandy and lutitic lenses may appear as evidence of complete sedimentation sequences of this environment. Thus, sedimentary features and geomorphological evidence point to an alluvial fan environment made of braided channels with a high capacity for lateral migration. This palaeonetwork driving the terrace aggradation has been partially identified on the terrace surface (Fig. 2). Sedimentary facies and sequences indicate the prevalence of sheetflooding processes (Blair and McPherson, 1994) during the depositional stage Qt1.

A complex multi-storey 3 m-thick calcrete identified on the Qt1 deposits represents a very advanced morphological stage (Sancho and Meléndez, 1992; Meléndez et al., 2011), indicating a long period of time for soil development according to regional soil chronosequences (Badía et al., 2009; Lewis et al., 2009). Hence, based on geomorphological and sedimentary features, the culminant Qt1 terrace of the Alcanadre River must be considered as a large alluvial fan terrace rather than a true fluvial terrace.

4.2. ESR ages

ESR age results obtained for the two sediment samples are given in Table 1. Regardless of the centre considered, ALC1201 and ALC1202 yield consistent ages at 1σ and indicate an Early Pleistocene chronology for the Qt1 terrace. Consequently, weighted mean age values of 1566 ± 145 ka and 1276 ± 104 ka may be calculated for the Qt1 terrace formation based on Al and Ti-centres, respectively. However, one may observe a systematic deviation between the two age estimates derived from each centre. Following the principle of the Multiple Centre approach, the older age estimates provided by the Al centre may be interpreted as evidence for an incomplete bleaching of the ESR signal prior to alluvial deposition, given its slower bleaching kinetics in comparison with the Ti centre. Consequently, ESR-Al age estimates should thus be observed as maximum possible ages. In contrast, the ESR-Ti age result of 1276 ± 104 ka may be reasonably considered as the most reliable estimation of the true age of the Qt1 deposits (Duval et al., 2015).

4.3. Palaeomagnetic data

AF demagnetization does not provide reliable results because of samples that are not completely demagnetized at 110 mT. Therefore, we only consider the TH results for both locations.

At the Qt1.1 site, the characteristic components are directed towards the origin of the orthogonal diagrams in 8 samples (Fig. 4, Table 2). The site provides a mean declination and inclination of 027 and 63 (α_{95} : 10 and k : 33). The unblocking temperature range is between 200 and 400 °C as a lower limit and 675 – 680 °C as an upper limit, suggesting hematite as the carrier of the natural remanent magnetization.

At Qt1.2, the average direction is also calculated from 8 samples with ChRMs directing towards the origin in the orthogonal diagrams (Fig. 4). The mean declination and inclination are 234 and -25 (α_{95} : 14 and k : 21), respectively. The unblocking temperature ranges between 200 and 250 °C and 550 – 675 °C, indicating again that hematite is the main carrier.

The occurrence of reversed polarity found in the Qt1 terrace of the Alcanadre River unambiguously points to the Matuyama age (s.l.) of this alluvial unit. However, normal polarity is also recorded in the same Qt1 terrace level. The simplest explanation considering the primary record of the magnetic field is that the terrace aggradation period would span along two different magnetic chrons: a portion of Matuyama chron but also during a subchron with normal polarity. If date, this could correspond to the Cobb Mountain subchron (~ 1.22 – 1.24 Ma after Ogg, 2012; 1.189 – 1.221 Ma after Singer, 2014). A similar deduction was achieved for the Cinca River (Sancho

Table 1

Dose rate and ESR age results obtained for the samples ALC1201 and ALC1202 (from Duval et al., submitted for publication).

Sample	ALC1201	ALC1202
Depth (m)	4 ± 2	14 ± 2
Assumed water content (%)	20 ± 5	18 ± 5
Internal dose rate ($\mu\text{Gy/a}$)	50 ± 30	50 ± 30
Alpha dose rate ($\mu\text{Gy/a}$)	18 ± 15	17 ± 14
Beta dose rate ($\mu\text{Gy/a}$)	672 ± 54	601 ± 53
Gamma dose rate ($\mu\text{Gy/a}$)	356 ± 33	256 ± 24
Cosmic dose rate ($\mu\text{Gy/a}$)	126 ± 44	37 ± 8
Total dose rate ($\mu\text{Gy/a}$)	1222 ± 97	961 ± 79
D_E (Gy) Al center	1827 ± 237	1535 ± 128
D_E (Gy) Ti–Li–H center	1566 ± 115	1221 ± 115
Age (ka) Al center	1504 ± 229	1606 ± 187
Age (ka) Ti–Li–H center	1282 ± 139	1269 ± 157

et al., 2007), where Jaramillo was interpreted in the uppermost terrace level.

5. Discussion

Dating the earliest fluvial morphosedimentary units in the Ebro Basin is crucial to understanding the landscape evolution of NE Iberia. Numerical dates (weighted mean age of 1276 ± 104 ka) supplied by the ESR techniques are supported by mapping, geomorphological features, soil development and palaeomagnetic data. These consistent data allow us to discuss new insights into the Early Pleistocene evolution of the Ebro Basin.

5.1. Palaeogeographical significance

The Alcanadre Qt1 terrace is made of an extensive aggradational sheet that records the earliest fluvial sedimentary activity in the central sector of the Ebro basin under exorheic conditions, after the capture of the Ebro palaeolake by the Mediterranean coastal network. Consequently, it represents a geomorphological landmark of high interest in the long-term landscape evolution of the northeastern Iberian Peninsula, and the first numerical dating of this Early Pleistocene alluvial terrace piedmont. Water divide position, alluvial fan morphology and sedimentary features indicate a very mobile, low hierarchical and poorly defined braided fluvial network at this time (Alberto et al., 1983). Analogous fluvial terraces are also identified in most valleys (Noguera Ribagorçana, Cinca and Gállego rivers) of the Southern Pyrenean sector of the Ebro Basin. The development of this alluvial fan terrace at approximately 1.3 Ma ago is interpreted as the end of a long period (several million years) of continuous fluvial denudation of the Tertiary bedrock initiated between 13 and 8.5 Ma ago when the Ebro Basin found its way to the Mediterranean (García-Castellanos et al., 2003), although this timing has recently been highly debated (Babault et al., 2006; Arche et al., 2010; Urgeles et al., 2011).

This earliest morphosedimentary pulse could be more or less synchronous, at least in the central sector of the Ebro Basin because the oldest staircase terraces of the Ebro River and its main tributaries (e.g., the Noguera Ribagorçana, Cinca and Gállego rivers) all outcrop at approximately 200 m above the active channel.

5.2. Palaeoclimate considerations

In the nearby Cinca River and the Gállego River valleys, which are fed by glaciated mountain headwaters, fluvial aggradation correlates with cold stages, with glacier advances triggering glacier outwash pulses with high water discharges and high sediment supplies downstream (Lewis et al., 2009; Benito et al., 2010). Late

Fig. 4. Stepwise thermal demagnetization diagrams: a) stereoplot projection in lower (black) and upper (white) hemispheres; b) orthogonal diagram (black: projection of magnetic declination, white: projection of magnetic inclination), and c) decay of the natural remanent magnetization at every thermal step. The characteristic component is also noted.

Table 2
Characteristic component for each studied sample calculated with Remasoft 3.0 (Chadima and Hrouda, 2006).

Outcrop	Sample	Declination	Inclination	MAD	Temperature range (°C)
Qt1.1	1c	360	66	7	200–680
Qt1.1	1d	15	64	11	200–680
Qt1.1	2a	7	57	7	400–680
Qt1.1	2b	29	61	5	400–675
Qt1.1	3b	33	76	11	400–680
Qt1.1	3c	20	76	11	350–680
Qt1.1	4a	48	46	10	400–680
Qt1.1	4b	43	49	11	450–680
Qt1.2	2a	246	–31	11	200–675
Qt1.2	4a	234	–23	4	200–625
Qt1.2	5a	255	–23	10	200–675
Qt1.2	6a	258	–23	12	200–675
Qt1.2	8a	272	–14	6	200–550
Qt1.2	10a	221	–24	11	200–675
Qt1.2	11a	218	–20	8	250–625
Qt1.2	12a	208	–20	7	200–650

MAD: maximum angular deviation.

Pleistocene terraces of the Alcanadre River, fed by a non-glaciated mountain headwater, were correlated to periglacial conditions favouring mechanical weathering, sparse vegetation and slope washout during prevailing cold and humid phases (Calle et al., 2013). Consequently, we would expect that the development of fluvial terraces in the Ebro basin was associated with or even triggered by the onset of high-amplitude stadial/interstadial fluctuations. In regions with climatic forcing of terrace formation, rivers have responded mainly to stronger 100 ka climatic cycles (Bridgland and Westaway, 2008; Pazzaglia, 2013). It has been well established in the palaeoclimatic literature that a fundamental change between 1250 and 700 ka ago, known as the Mid-Pleistocene transition (MPT), occurred when the dominant periodicity of climate cycles changed from 41 ka to 100 ka (Lisiecki and Raymo, 2005) in the absence of substantial change in orbital forcing (Shackleton, 2000). At this time, an increase occurred in the amplitude of change of deep-ocean foraminifera oxygen isotopic ratios, which is traditionally interpreted as defining the main rhythm of ice ages (e.g., Gibbard and Cohen, 2008). Different compilation studies noted that changes in the overturning circulation (Lisiecki, 2014) and/or the expansion of Antarctica ice-sheet volume (Elderfield et al., 2012) may be behind this important global

change that initiated the MPT. In the Western Mediterranean realm, the master marine core used to reconstruct climate during the MPT is the ODP976 in the Alboran Sea, where the planktonic $\delta^{18}\text{O}$ record (Von Grafenstein et al., 1999), reconstructed SST (González-Donoso et al., 2000) and pollen data (Joannin et al., 2011) characterize more intense and prolonged glacial states with associated subsequent rapid deglaciations during the MPT.

Therefore, the age of Qt1 in the Ebro basin at 1276 ± 104 ka allows us to associate the beginning of the Early Pleistocene morphosedimentary fluvial activity in the Ebro Basin under exorheic conditions with a fundamental change in glacial-interglacial periodicity and amplitude with drastic geomorphic consequences in the northeastern Iberian Peninsula.

5.3. Fluvial incision rates

Fluvial incision predominated in the Pyrenees and Ebro basin in a time under exorheic conditions in a post-orogenic environment. Nevertheless, this regional tendency is altered over very short periods of fluvial aggradation (Fuller et al., 1998; Lewis et al., 2009). The resulting geomorphic expression is a staircase strath terrace system developed in both the northern and the southern sides of the central Ebro Basin. Strath terraces (Bull, 1991) are frequently used to calculate rates of stream incision under different geodynamic contexts (e.g., Wegmann and Pazzaglia, 2009). In the Alcanadre River valley, starting from the Qt1 terrace, the fluvial incision may be estimated from the combination of the available topographic (digital elevation model MDT05/MDT05-LIDAR) and chronological (ESR dating) data, and ranges from 157 ± 13 mm/ka (1σ) in the proximal sector of the terrace to 125 ± 10 mm/ka (1σ) in the distal sector. Final 1σ errors were derived from the combination of the individual errors in the mean age (8.15%) and in the altitudes (<0.5%). These estimated rates clearly point to a divergence upstream when both the Qt1 terrace and the Alcanadre active channel profiles are compared.

The calculated rates of fluvial incision must be explained in terms of coupled regional climate and uplift (e.g., Whipple and Tucker, 1999; Schlunegger and Hinderer, 2001; Hartshorn et al., 2002; Vandenberghe, 2003; Zaprowski et al., 2005; Gibbard and Lewin, 2009; Wegmann and Pazzaglia, 2009; Westaway et al., 2009; Stokes et al., 2012; Pazzaglia, 2013a,b). It is difficult and controversial to precise the factors controlling fluvial downcutting.

Preliminary data from terraces in the Cinca River valley (Pyrenees and the adjacent Ebro Basin, NE Spain) provided by Sancho et al. (2012) suggest changes in incision rates along the river valley but also through time. In a broad way, several mechanisms could be involved to explain the fluvial incision pattern in NE Iberia: i) regional uplift related to isostatic adjustment resulting from crustal thickening (Casas-Sainz and de Vicente, 2009; Fernández-Lozano et al., 2011), to erosional unloading (García-Castellanos et al., 2003; Stange et al., 2014) and/or to mantle dynamics (Lewis et al., 2000), ii) isostatic orogenic rebound affecting the Pyrenees (Gunnell et al., 2008) and iii) fluvial erosivity controlled by Pleistocene climate changes (Lewis et al., 2009).

The calculated mean fluvial entrenchment rate in the central sector of the Ebro Basin is higher than in other extensive Iberian Neogene basins in Central Iberia drained by Atlantic rivers, even though it is worth highlighting the scarcity of the data available. For example, the mean fluvial incision rate in the Duero Basin was estimated to be approximately 64.9 ± 8.9 mm/ka from a terrace of the Arlanzón River that is 1.14 ± 0.13 Ma old and outcrops at 70–78 m above the active channel (Moreno et al., 2012). However, this incision rate must be interpreted as a minimum value, simply because this ESR age result is derived from the measurement of the Al centre alone and should thus be considered as a maximum possible age. In the Tagus Basin, Silva et al. (2013) roughly extrapolated a fluvial incision rate of 50 mm/ka for terraces aged between 1.1 and 0.65 Ma in different river valleys, but numerical ages are very limited for this area. In contrast, higher incision rates from the Lower Tagus River (Portugal) are been reported. From the oldest terrace (903 ± 58 ka) the average incision rate is near 100 mm/ka approximately (Rosina et al., 2014). Furthermore, estimation of time-averaged incision rates of 70–100 mm/ka over the last 2.6 Ma in the area is also provided by Cunha et al. (2008). Nevertheless, these rates increase locally in active tectonic areas of the Lower Tagus Basin (Martins et al., 2009). These variable incision rates between the Iberian Meseta basins (Duero and Tagus basins) and the Mediterranean Ebro basin during the Quaternary could result from the differential isostatic uplifting as a response to the Tertiary and recent compression in the Iberian Plate and the Neogene extension in the Mediterranean margin, respectively (Casas-Sainz and de Vicente, 2009; Fernandez-Lozano et al., 2011). However, such large scale correlations are also for the moment strongly limited by the scarcity of the numerical ages available. It is now quite clear that a major effort should be centred on the improvement of the chronostratigraphic framework of all of the Early Pleistocene terraces identified in the Iberian Peninsula.

Considering the altitude of the youngest Tertiary rocks preserved in the Central Ebro Basin (Monte Oscuro and San Caprasio, 812 m asl), and assuming a theoretical scenario of Quaternary steady fluvial entrenchment, we may estimate that the onset of the erosive activity related to the transition from endorheic to exorheic conditions in the central sector of the Ebro Basin did not start before than 3.2 Ma.

6. Conclusions

The numerical dating of Early Pleistocene alluvial and fluvial morphosedimentary units is one of the major challenges to understanding the landscape evolution of the Neogene basins in Iberia. The present study significantly improves the Early Pleistocene chronostratigraphic framework of the fluvial terrace sequences in the Ebro Basin. We present a numerical age (1276 ± 104 ka) for the earliest unit of the Alcanadre River staircase terrace system based on the ESR technique, which is also consistent with palaeomagnetic data. To our knowledge, this is the oldest numerical date in a terrace of the Iberian Peninsula. The studied

alluvial level Qt1 indicates that the drainage network during the Early Pleistocene was poorly defined and was characterised by a wide alluvial fan piedmont with alluviation in response to obliquity-driven 41 ka climatic cycles. The Qt1 morphosedimentary unit represents a unique alluvial vestige of the critical palaeoclimatic changes experienced during the Mid-Pleistocene Transition (~1 Ma) when climate fluctuation shifted to 100 ka climatic cycles. Subsequent fluvial evolution is characterized by major entrenchment of fluvial valleys and staircase terrace formation associated with stronger stadial/interstadial oscillations. This change from Early Pleistocene wide aggradation alluvial systems to the Middle-Late Pleistocene entrenched fluvial valleys agrees with the fluvial evolution models described in other regions of central and NW Europe. Since the Early Pleistocene, the average fluvial incision rate ranges between 157 ± 13 and 125 ± 10 mm/ka in the Ebro Basin, which is apparently significantly higher than other estimations made for other Atlantic Iberian basins. However, more numerical data for the earliest terraces are necessary to better understand the landscape evolution and the palaeogeographical transition from endorheic to exorheic conditions in the Ebro Basin and other Iberian Cenozoic basins.

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