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Climatic implications of the Quaternary fluvial tufa record in the NE Iberian Peninsula over the last 500 ka

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Abstract

Drainage of the Iberian Ranges (NE Spain) houses one of the most extensive Quaternary fluvial tufaceous record in Europe. Specifically tufa deposits in the Añamaza, Mesa, Piedra and Ebrón river valleys were mapped and stratigraphically described. In addition they were chronologically referenced from a large dataset of U/Th disequilibrium series, Aminoacid Racemization and Radiocarbon dates to infer long-term climatic fluctuations in NE Iberia over the past 500 ka. High consistency among the dating methods, also supported by geomorphic and stratigraphic relations was observed. Tufa deposits accumulated in cascades, barrage-cascades and related damming areas developed in stepped fluvial systems of variable slope, that display sequences of cut-and-fill and nested-fill terraces. Tufa accumulation occurred during discrete multi-millennial time periods along the Middle and Upper Pleistocene and

Holocene. Maximum frequency of tufa deposition was identified at 120 ka (MIS-5e), 105 ka (MIS-5c), 85 ka (~ MIS-5a) and 7 ka (MIS-1), probably under warmer and wetter conditions than today. Additional phases of tufa deposition appear at ~ 345 ka (~ MIS-10), 284 ka (MIS-9a), 206 ka (MIS-7) and 154 ka (MIS-6). Although most tufa growth episodes are clearly correlated to interstadial periods, it is remarkable the occurrence of tufa activity during the Penultimate Glaciation (MIS-6), indicating that the onset of this stage was climatically favorable in the Iberian Peninsula. Biostatic conditions and dynamics of karstic systems regulating tufa deposition seem to be very sensitive to 1) precipitation regime, controlled by shifts in the position of North Atlantic atmospheric belts and 2) summer insolation, regulated by orbital forcing.

Key words: fluvial tufas, dating techniques, Quaternary climate, Iberian Ranges.

1 Introduction

Tufas are terrestrial freshwater deposits of calcium carbonate (Viles and Goudie, 1990) in karstic terrains, containing remains of macro- and microphytes, invertebrates and bacteria (Ford and Pedley, 1996). They could be considered as the external sedimentary response to karstic systems dynamics. A close relationship between karstic activity, including tufa formation, and environmental conditions is established in terms of suitable temperature, water availability, vegetation expansion, soil development, carbonate dissolution after infiltration and water discharges saturated in calcite (Henning et al., 1983; Magnin et al., 1991; Baker et al, 1993; Martín-Algarra et al., 2003; Domínguez-Villar et al., 2011; among others). As a consequence, tufa records become a useful tool to decipher long-term/low-frequency Quaternary climatic changes because they can be accurately placed in time by using several dating techniques.

Palaeoclimate interpretation of tufa archives (Ford and Pedley, 1996; Pedley et al. 1996) seems to indicate that temperature is the limiting factor in temperate areas of high latitudes (Pazdur et al., 1988; Pedley, 1993; Frank et al., 2000), while precipitation could limit tufa formation in low latitude regions (Livnat and Kronfeld, 1985; Kronfeld et al., 1988; Smith et al., 2004; Viles et al., 2007; Cremaschi et al., 2010). In fact, Henning et al. (1983) proposed a different pattern in the frequency of tufa formation under both temperate and Mediterranean environments. This simple pattern becomes more complex in the Iberian Peninsula due to its intermediate latitudinal location as well as because of its highly sensitivity to shifts in the location of the North Atlantic atmospheric belts (Calvo et al., 2001; Cacho et al., 2002; Moreno et al., 2005; Eynaud et al., 2009). In this way, paleoclimate information derived from the fluvial tufa record in the northeastern Iberian Peninsula can significantly contribute to improve the available palaeoenvironmental framework at Mediterranean scale during Quaternary times.

Tufas are found in a wide range of karst environments around the world and are very common in Alpine Ranges of the Mediterranean region reaching great relevance in the Iberian Peninsula (Durán, 1989; Pentecost, 1995; Ford and Pedley, 1996; Pedley, 2009). Specifically the Iberian Ranges (NE Spain) house an exceptional tufa record trough time and space mainly associated with low and medium order reaches of the fluvial network. Although the palaeoenvironmental studies of Iberian Ranges tufas have recently experienced a significant impulse (e.g. Ortiz et al., 2009; Domínguez-Villar et al., 2011; Vázquez-Urbez et al., 2011a), these advances can be supplemented with new data. This study contributes to improve the palaeoclimatic information in northeastern Iberian Peninsula by using a compilation of chronological data from Quaternary fluvial tufa records in the Añamaza, Mesa, Piedra and Ebrón rivers valleys.

Palaeoenvironmental implications derived from tufaceous archives, supported by a new chronological database by using U/Th series dating, Aminoacid Racemization and Radiocarbon, have been inserted in the Middle-Upper Pleistocene and Holocene regional paleoclimatic context. At the moment, only glacial and fluvial archives has been used to infer cold signatures within a biased palaeoenvironmental scenario (Fuller et al., 1998; Lewis et al., 2009; Benito et al., 2010; Calle et al., 2013; García-Ruiz et al., 2013). Besides, the deduced long-term (multi-millennial) climatic changes have been correlated with the Quaternary climate pattern at both Mediterranean and global scale. Preliminary chronological data and paleoclimatic interpretation of local tufa records from the studied sector of the Iberian Ranges has been supplied by Arenas et al. (2010), Sancho et al. (2010) and Lozano et al. (2012).

2 Studied areas in the Iberian Ranges

The Iberian Ranges are a NW-SE trending alpine intraplate mountain chain located in north-eastern Iberian Peninsula (Fig. 1). This mountain range is about 500 km in length reaching the Mediterranean coast. The highest peaks exceed 2300 m in altitude.

The landscape is dominated by extensive high altitude platforms and planation surfaces at 1600-1000 m a.s.l., partitioned by tectonic grabens. The most extensive planation surface is named *Superficie de Erosión Fundamental* of the Iberian Ranges (Peña et al., 1984). Its development could be finished in Pliocene times (Gutiérrez and Peña, 1994). It erodes the alpine compressional structures affecting thick and extensive marine carbonate formations, Jurassic and Upper Cretaceous in age. An intensive karstic period leading large fields of dolines and poljes occurred during the final stage of the planation surface development. The resulting erosive surface was partitioned by extensional tectonics during Pliocene and Quaternary times (Gutiérrez and Peña, 1994). In addition, the resulting morphotopographic framework constitutes the starting point for the subsequent fluvial downcutting during Quaternary (Gutiérrez et al., 2008; Scotti et al., 2014).

Thus, the formation of tufas in the Iberian Ranges was triggered by the occurrence of high altitude, extensive limestone flattened areas, partitioned by neotectonics and dissected by a fluvial network with non-equilibrium longitudinal stretches, steep gradients and marked knick points. Under this morphostructural framework, tufa accumulation was increased during favourable intervals with high water discharges saturated in calcite from karstic aquifers and warm environmental conditions.

In the Iberian Ranges, the most important tufa build-ups are associated with the drainage network flowing radially to the N and NE (into the Ebro depression), to the SW (into the Tajo and Guadiana depressions) and to the SE (into the Mijares, Turia and Júcar depressions). The Quaternary fluvial tufa records studied are located in the valleys of the Añamaza, Mesa and Piedra rivers, tributaries of the Ebro River, and the

Ebrón River, a tributary of the Turia River (Fig. 1) distributed from the northwestern sector to the central sector of the Iberian Ranges.

The Añamaza valley is located in the northwestern sector of the Iberian Ranges (Fig. 1). The Añamaza River is a 37 km-long tributary of the Alhama River, which in turn flows into the Ebro River. It drains an area of around 210 km^2 with an altitude ranging between 1040 and 460 m. The mean annual temperature is 11.2 ºC and the mean annual precipitation is 520 mm. The geological bedrock (Fig. 2a) is composed of Middle Jurassic marine limestones and marls and Upper Jurassic-Cretaceous continental and transitional rocks (Weald facies), affected by folds and faults with NW-SE trends. Continental Tertiary detrital and limestone deposits overlie the sequence. The River Añamaza is fed mainly from a karstic aquifer hosted in Dogger limestones of 200 m maximum thickness. Springs are mainly found between Añavieja and Débanos. A mean annual discharge around 0.16 m^3/s is recorded at Débanos. Current tufa sedimentation has been reported by Auqué et al. (2014).

The Mesa and Piedra valleys are located in the northern side of the central sector of the Iberian Ranges (Fig. 1). Both rivers join in the La Tranquera Reservoir and are tributaries of the Jalón River, which in turn flows into the Ebro River. The Mesa River flows along 50 km with a general northeast trend. The surface of the drainage basin is 622 km^2 and the altitude ranges between 1520 and 690 m. Mean annual temperature is 13 ºC, with strong seasonal contrasts. Mean annual precipitation is 410 mm, irregularly distributed. The river flows across Triassic sandstones, dolostones and gypsum, Jurassic and Cretaceous limestones and dolostones and Miocene conglomerates, sandstones and mudstones (Fig. 3a). Jurassic and Cretaceous rocks hold the regional aquifer that feeds the drainage network in the area. Mean discharge of the River Mesa reaches 1.58 m^3/s including low-thermal groundwater inputs in the lower valley stretch. Present day tufa sedimentation and hydrological conditions in the Mesa River has been analyzed by Auqué et al. (2013).

The River Piedra flows along 41 km with a north trend. Its drainage area occupies some 1545 km^2 and its altitude ranges from 1010 to 600 m. The mean annual air temperature recorded in the area is 13.7 ºC and the mean annual precipitation reaches

370 mm. The bedrock (Fig. 3a) is composed of Jurassic limestones, Lower Cretaceous sands and sandstones, and a thick Upper Cretaceous sequence of limestones and dolostones. All these units are slightly deformed by NW–SE trending folds and faults. Continental Tertiary detrital deposits overlie the sequence. The River Piedra is fed mainly by groundwater from an aquifer hosted in Lower Jurassic and Upper Cretaceous limestones and dolostones some 500 m thick. The mean discharge of the River Piedra is around 1.22 m^3/s. Current tufa dynamics in the Piedra has been intensively studied over last 13 years (Vázquez-Urbez et al., 2010; Osácar et al., 2013; Arenas et al., 2014a).

The Ebrón valley is located in the southeastern sector of the Iberian Ranges (Fig. 1). The Ebrón River, 30 km long, is a tributary of the Turia River on the Mediterranean side of the Iberian Peninsula. Its drainage area is around 246 km^2 and the altitude range between 1720 and 720 m. Mean annual temperature in the area is around 10.8 ºC, with strong seasonal contrasts, and a mean annual precipitation reaches 450 mm, irregularly distributed. Geological bedrock (Fig. 4a) is made of Triassic dolostones, mudstones and gypsum rocks, Jurassic limestones, Lower Cretaceous detrital rocks and Upper Cretaceous dolostones. These materials are affected by NE-SW and NW-SE trending folds and faults. Tertiary conglomerates, sandstones and mudstones overlie the Mesozoic sequence. Mean discharge of the Ebrón River, around of 1.20 m^3/s, is mostly derived from groundwater contributions in the middle reach of the valley, near El Cuervo village.

3 Material and methods

The chronological study of Quaternary tufa records requires a geological mapping approach, as well as a detailed geomorphic and stratigraphic control of the identified tufa build-ups, prior to sample and to perform dating techniques. In a first stage, geological mapping of tufa outcrops along the Añamaza, Mesa, Piedra and Ebrón valleys was undertaken on an aerial photographic base (1:18,000 scale). Later, intensive field work was carried out to check the mapped tufa build-ups, to distinguish morphosedimentary units, to describe selected stratigraphic sections and, finally, to sample for dating. A multi-technique strategy, including U/Th disequilibrium series

(U/Th), Aminoacid Racemization (AR) and Radiocarbon (^{14}C) methods was developed according the tufa facies characteristics and the expected age of the deposits. A total of 93 dates are presented. As all of them do not have the same level of reliability and uncertainty two techniques have been applied simultaneously on the same stratigraphic section, when possible. Sometimes replicated ages have been obtained. Although discrete ages of individual tufa samples may be subject to selection biases, the set of samples from a particular build-up allows to constrain the time elapsed for its accumulation. As a consequence, the whole population of data appears to be representative of the major stages of tufa formation in the Iberian Ranges.

3.1 U/Th disequilibrium series

Uranium-Thorium disequilibrium dating was performed using parallel ion-counting multi-collector ICP-MS (Hellstrom, 2003; Cheng et al., 2013). A total of 35 samples from tufa build-ups outcropping in the valleys of the four rivers were developed (Table 1). Samples correspond to various facies: stromatolites, boundsones of mosses, calcite coatings on phytoclasts and bioclastic mudstones and wackestones, in all cases avoiding cements. Quality of data is variable, according the initial amount of detrital Th, the post-depositional locking of the geochemical system and the recrystallization processes. Many samples show contamination with external Th. In these cases, corrected ages for detrital Th were calculated according Hellstrom (2006). In open systems the post-deposition uranium mobility usually leads to U loss, which makes samples appear older than they really are (as the Th/U ratio is increased). Taking account the closeness to closed systems, the reliability of results is variable. In some cases, replications indicate high quality data. Despite the inconveniences observed in the application of U/Th on tufa deposits, the obtained ages contribute to establish a reasonably accurate chronological framework.

3.2 Aminoacid Racemization

A total of 48 samples from tufa build-ups located in the four fluvial valleys were analyzed by AR techniques (Table 2). Samples correspond to carbonate silts and sands. Ostracode specimens from various species were recovered, although we selected mostly *Herpetocypris reptans* for the analysis because it is the most common in tufa deposits of the Iberian Peninsula. In some few cases, where *H. reptans* was absent or scarce, *Cyprideis torosa, Candona neglecta*, *Candona marchica* and *Ilyocypris gibba* shells were picked. Moreover, the age calculation algorithms were calculated for these species (Ortiz et al., 2004). However, due to certain genera show different amino acid racemization rates (Ortiz et al., 2013), a conversion factor had to be applied to D/L ratios of these three species in order to be directly comparable with *H. reptans* aspartic and glutamic DL values. When possible, we performed 7 analyses of the same sample. Ostracode valves were carefully cleaned sonically in distilled deionized water and rinsed in the same water to remove sediment. In order to remove secondary organic molecules adsorbed to the shells, the valves were then submerged in 3% hydrogen peroxide for 2 hours following Kaufman (2000) and Hearty et al. (2004).

Aminoacid concentrations and ratios were quantified using HPLC (high-performance liquid chromatography), following the sample preparation protocol described by Kaufman and Manley (1998) and Kaufman (2000).

We measured D/L ratios of aspartic acid and glutamic acid because in most ostracode valves they account for over ca. 50% of the amino acid content (Kaufman, 2000; Bright and Kaufman, 2011). Likewise, they have high racemization rates, thus making them suitable to date relatively young samples. The numerical age of each sample was determined by introducing the aspartic acid and glutamic acid D/L ratios obtained in ostracodes into the age calculation algorithms established by Ortiz et al. (2004). The age of a sample is the average of the numerical dates. The age uncertainty is one standard deviation of all the numerical ages calculated from the amino acid D/L ratios of each sample.

The use of the age calculation algorithms obtained in central and southern Spain ostracodes by Ortiz et al. (2004) for the dating of these deposits is justified because a similar thermal history can be inferred for these areas, which are located in the Mediterranean climatic zone of the Iberian Peninsula, with a similar CMAT (current mean annual temperature). Likewise, the age calculation algorithms were established for the ostracode species analyzed here (*C. torosa* and *H. reptans*), which show similar racemization rates (Ortiz et al., 2013) and, therefore, DL ratios are directly comparable without any conversion factor.

3.3 Radiocarbon

Radiocarbon dating was performed on 10 samples taken from different tufa build-ups outcropping in the four valleys (Table 3). Samples correspond to gray peaty intervals and charcoal remnants. Occasionally gastropods and eggshells were also dated. The dating analyses were carried out by the Radiocarbon Laboratory of the Department of Geography at the University of Zurich. The AMS (accelerator mass spectrometer) used was the tandem accelerator of the Institute of Particle Physics at the Swiss Federal Institute of Technology Zurich. Radiocarbon dates were calibrated using the Calib6 program and the IntCal09 calibration curve (Stuiver and Reimer, 1993; Reimer et al., 2009).

4 Results

4.1 General stratigraphic and sedimentological features of fluvial tufas

Fluvial tufa deposits appear as successive build-ups that crop out along the main, and some secondary, valleys as stepped terraces in longitudinal profiles as well as transverse sections. In all cases, tufa morfosedimentary units lie unconformably on the bedrock conforming sequences of cut and fill and nested fill terraces. Commonly, these build-ups are composed of lenticular and wedge-shaped bodies that open downstream, with lenticular (channel-like) transverse sections. The thickness of single build-ups ranges from a few meters up to 90 m, and their extent can reach approximately 1.5 km long and several hundred meters wide.

A wide variety of sedimentary facies make these deposits (Figs. 5a, 6a, 7a and 8a): stromatolites (Ls), boundstones of bryophytes (Lbr) and of other macrophyte stems (up-growing plants, Lst 1; down-growing plants, Lst 2), rudstones of phytoclasts (Lph) and of oncoids (Lo), mudstones to packstones of bioclasts and intraclasts (Lb), marls (M) and carbonate, mainly bioclastic, sands and silts (Sb). The latter two facies may contain variable amounts of microscopic and macroscopic organic matter, in some cases making up to peaty intervals. Gravels, conglomerates (G), sands, sandstones (S) and mudstones (F) are minor components; typically, coarse facies appear related to erosional surfaces.

Facies Ls, Lbr and Lst 2 constitute highly inclined to vertical strata, which, in most cases, make up hemi-domed bodies up to several metres high. Lenticular bodies of phytoclastic facies (Lph) are commonly interbedded. All these facies formed in typically fast flowing water conditions: cascades, barrage-cascades and moderate-sloped river stretches. In contrast, facies Lb, Sb, Lph, M and minor Ls and Lo mostly compose horizontal and slightly inclined strata. Facies Lb, Sb, Lph, Lo and M formed in slow-flowing and standing-water areas, dammed by barrage-cascades. Oncolites can also be structured as shallow, low-sinuosity bars. Stromatolites developed also in moderate-sloped river stretches between cascades. Boundstones of up-growing plants (Lst 1) formed in moderate- to slow-flowing water conditions both along free-flowing river stretches and standing-water areas (e.g., palustrine conditions) (Arenas-Abad et al., 2010; Vázquez-Urbez et al., 2012). Coarse detrital facies (G, S and Lph) appear related to erosional surfaces at the base of the build-ups, but also within them giving rise to composite build-ups (i.e., made of several lenticular and wedged bodies) (Vázquez-Urbez et al., 2012; Arenas et al., 2014).

The geometry of deposits, facies associations and lateral relations among facies within buid-ups conform the barrage-cascade model (Pedley, 1990; 2009) or stepped fluvial system (Arenas-Abad et al., 2010), consisting of cascade and barrage-cascade structures laterally related to dammed areas. However, distinct attributes characterize each of the studied fluvial systems, mostly as a function of variations in slope along the valley and as the result of existing diffluence processes. The Añamaza deposits correspond to both moderate and very high-sloped fluvial systems, which determined, respectively, the presence of large pooled areas (e.g., in the upper part of the valley) and of steep river stretches dominated by facies Ls and Lbr (e.g., in the middle part of the valley) (Arenas et al., 2014). In the Mesa valley, the moderate slope conditioned the development of large dammed areas, with wide palustrine fringes, separated by barrage-cascades. In contrast, the outstanding feature of the River Piedra tufas is the abundance of thick barrage-cascade deposits in the middle-low stretch, as a result of increased slope. At some moments, the height of the barrages surpassed the water divide and caused the upstream dammed areas to spill over a secondary course (fluvial diffluence mechanism), which also recorded tufa deposits (Vázquez-Urbez et al., 2011, 2012). In the Ebrón valley, with moderate to high slope, thick deposits of facies Sb formed in dammed areas upstream of barrage-cascades. In addition, extensive development of stromatolites occurred in some gently sloped stretches between barrages (Lozano et al., 2012).

In brief, the studied tufa deposits formed in stepped fluvial systems of variable slope, as a result of alternating stages of valley filling and erosional processes, which produced successive build-ups along the main and secondary valleys.

4. 2 Tufas of the Añamaza River valley

Tufa deposits crop out along the middle stretch of the Añamaza valley (northeast of Dévanos) (Figs. 2a). Quaternary tufa build-ups are distributed in two main morphosedimentary units forming a staircase terrace system. The thickness is variable reaching 70 m in the Salto del Cajo build-up (Fig. 2b). Most common tufa facies are macrophyte boundstones and rudstones, moss boundstones, stromatolites, carbonate sands and silts (Fig. 2c), and bioclastic mudstones, wakestones, packstones and floatstones.

Some selected build-ups were sampled for dating (A-1, A-2, A-3, A-4, A-5, A-6, A-7, A-8, A-9 and A-10) (Fig. 2a). Data from U/Th show variable reliability because some of them represent open geochemical systems. In addition, corrected ages considering the occurrence of detrital Th introduce small changes to the final proposed age (Table 1). Respect to AR age data, only some samples show certain recent contamination (Table 2).

The Salto del Cajo build-up (Fig. 2b) (A-4 to 8 sections; Fig. 5a and b) is a wedge-shaped body that opens northwards. It is made of five depositional bodies separated by erosional surfaces composing a complex filling of a steep stretch (Arenas et al., 2014). A broad agreement between chronological data (U/Th and AR) and the stratigraphic correlation among stratigraphic sections was observed. Thus, considering the reliable data, the first depositional stages are dated as 282.5 ± 7 ka (U/Th sample SC1-2) and 204.3 ± 6.7 ka (U/Th sample SC4-2r), and the rest of the depositional stages are dated between 120.8 ± 3.8 ka (U/Th sample SC2-11) and 80.5 ± 16.6 ka (AR sample SC2-16). In addition, a cascade tufa unit that overlies previous Pleistocene deposits yielded an age of 1.5 ± 0.2 ka (U/Th sample SC5-1r).

In the Las Parideras sector (A-3 section) a wedge-shaped tufa build-up, approximately 17 m thick, has been dated. The approximate age of this outcrop could be between 83.5 ± 18.9 ka (AR sample AÑA13-1) and 105.8 ± 3.9 ka (U/Th sample AÑA 13-2). Two other build-ups (A-10 and A-9) (Fig. 5a) located in the northern part of the studied Añamaza valley stretch provide reliable ages of 115.4 ± 33.0 ka (AR sample AÑA 7N-8) to 99.6 ± 1.8 ka (U/Th sample AÑA 7N-15) for A-10 section, and 129.1 ± 16.8 ka (AR sample AÑA 8-4), 121.7 ± 27.0 ka (AR sample AÑA 8-3) and 119.1 ± 2.5 ka (U/Th sample AÑA 8-5) for A-9 section (Fig. 2c). A sample (AÑA 8-1) of this build-up gave a U/Th age with a great uncertainty of 337.0 ± 110.1 ka.

Other tufa build-ups encased in Pleistocene tufas are those of El Molino (A-2 section) (Fig. 5a) and Dévanos (A-1 section). Several samples yielded AR ages of 10.6 ± 3.3 and 10.5 ± 4.4 ka in Dévanos, and between 7.7 ± 3.8 ka and 3.3 ± 0.9 in El Molino (Table 2). Besides, an age of 1816-1509 ka (sample AÑA-M-H) has been obtained by calibrated radiocarbon in El Molino (Table 3). Correlative fluviolacustrine sediments studied by Luzón et al. (2011) from drilling cores in the upper stretch of the valley span from 10.6 ka to 0.6 ka.

In summary according to the obtained ages several episodes of tufa deposition correlated to marine isotope stages MIS 9a, 7, 5 and 1 respectively can be inferred. The presence of MIS 10 is uncertain. Most tufas in the River Añamaza valley formed during MIS 5 (130-80 ka) (Figs. 5a and 9a).

4.3 Tufas of the Mesa River valley

Tufa build-ups crop out scattered along 30 km in the River Mesa valley from Mochales to Ibdes villages (Fig. 3a). The thickness of single build-ups ranges from a few metres to

25 m. The build-ups can be grouped in two generations developing staircase terraces. Several build-ups belonging to the older stage have been chronologically characterized (Valdetechada, M-1 section; Jesus Nazareno, M-3 section; Los Villarejos, M-4 and M-5 sections; and La Rinconada, M-6 section). In addition, two other younger build-ups have also been dated near Villel de Mesa village (M-2 section). Most common tufa facies are macrophyte boundstones and rudstones, moss boundstones, stromatolites, carbonate sands and silts, and bioclastic mudstones, wakestones, packstones and floatstones.

The Valdetechada build-up (M-1 section) (Fig. 6a), located upstream of Mochales, is 15-20 m thick. Three samples were dated by AR (Table 2), yielding ages 110.4 ± 22.4 ka (sample BVT-A), 215.5 ± 31.6 ka (sample BVT-C) and 194.5 ± 24.1 ka (sample BVT-D). The former sample (BVT-A) is contaminated with recent aminonacids and, therefore, the age should be older. In the Los Villarejos Norte outcrop (M-4 section) (Figs. 3b and 6a), the AR ages obtained for two laterally related samples (LVN-A and LVN-B), located at the top of the build-up, are 74.1 ± 12.6 ka and 80.9 ± 11.2 ka respectively. These dates are consistent with two ages obtained by U/Th in the Casas Villarejos profile (M-5 section) (Fig. 6a) from samples located in very close stratigraphic position. This method supplied two accurate and precise ages, 80.9 ± 1.5 ka and 81.1 ± 2.0 ka (Table 1). In addition, another sample (JNE1.1) from the Jesús Nazareno stratigraphic section (M-3 section) (Fig. 6a and b) gave an age of 98.7 ± 0.6 ka, close to the above datings. Finally, the lower interval of the La Rinconada stratigraphic section (M-6 section) (Fig. 6a), near Ibdes village, was dated by AR (Table 2). The obtained ages are 129.1 ± 20.2 ka and 102.8 ± 21.7 ka (samples LR-A and LR-B). Nevertheless, these ages should be older because samples are contaminated with recent aminoacids.

The younger stage of tufa development has been studied in two outcrops located upstream and downstream of Villel de Mesa village (Fig. 3) and dated by AR. Upstream of Villel de Mesa the dated outcrop has an age of 8.4 ± 2 ka (sample RM1-A, Table 2). In the outcrop downstream of Villel de Mesa (M-2 section) (Fig. 6a), the obtained ages are 46.8 ± 8.2 ka (sample CMI-A), 6.7 ± 2.3 ka (sample CMI-B) and 13.7 ± 5.9 ka (sample CMI-C) (Table 2). Another sample (CMI-D), stratigraphycally equivalent to CMI-A, provided a calibrated ^{14}C age of 6400-6278 years BP (Table 3). Thus, the AR results indicate that this technique does not offer precise ages for Holocene times.

Briefly, considering the proposed ages for the studied tufa build-ups in the River Mesa valley, several stages of tufa development could be differentiated (Figs. 6a and 9b). The oldest phase (215-194 ka) correlates to MIS-7. The more important stage (130-75 ka) coincides with the whole MIS-5. It may be that the end of the MIS-6 is also recorded in this tufa deposition period. The occurrence of MIS 3 has been, locally, evidenced. Finally, the youngest phase is Lower Holocene in age (6-7 ka) (MIS-1).

4.4 Tufas of the Piedra River valley

Fluvial tufa deposits are very extensive and thick in the lower stretch of the Piedra River valley. They are basically located in two sectors: near the Monasterio de Piedra Natural Park and around Nuévalos village (Fig. 3a). From a morphosedimentary point of view several episodes of tufa formation arranged in cut-and-fill and nested-fill terrace patterns were distinguished.

Several tufa build-ups were studied and sampled. According to geomorphic and stratigraphic criteria they were grouped in an older period (La Requijada,P-3, P-4, P-5 sections; Barranco de Los Arcos, P-6 section; Los Bancales, P-2 section; Ermita de la Blanca, P-7 section; Monasterio, P-9 section; and Nuévalos Viejo, P-10 section) and a younger period (Arco de la Yedra, P-1 section; Cola de Caballo and Piscifactoría, P-8 sections). A great variety of facies is present.

The obtained U/Th ages are of variable quality. Some samples suffer badly from initial thorium contamination as well as from open system behavior (Table 1). Nevertheless, as a rule, the proposed ages, once corrected for initial thorium contamination, are reliable. A few cases form the AR analysis show signs of recent aminoacid contamination (Table 2).

Several tufa build-ups were studied near the Monasterio de Piedra, related to the River Piedra but also to the tributary network. The U/Th age obtained for the Monasterio build-up (P-9 section) (Fig. 7a) is 340.7 ± 15.6 ka (sample MON Top). The La Requijada tufa build-up (P-3, P-4 and P-5 sections) (Figs. 3c and 7a) is some 75 m thick and in which two main overlapped stages of tufa aggradation, separated by an important erosional surface, were identified. Deposits corresponding to the older stage were dated by AR (sample RS-1-C) and an age of 237.9 ± 27.4 ka was obtained. Tufas of the younger stage were also dated and a U/Th age of 174.1 ± 22.6 ka was yielded by sample RS-2.2b. The AR ages in this stage are 143.2 ± 28.8 ka and 194.5 ± 27.8 ka (samples RS 1-B and RS 1-A), even both samples two show evidence of recent aminoacid contamination (Table 2). The Barranco de los Arcos deposits (P-6 section) crop out as several isolated build-ups (Fig. 7a) that reach 20 m in thickness. Two replicated U/Th analysis of a sample (BLA-1.1 and BLA-1.2) have provided ages of 254.7 ± 48.5 ka and 229.3 ± 35.0 ka respectively. These deposits where, thus, correlated with the lower section of the La Requijada build-up. This result, along with mapping data, allowed reporting a fluvial diffluence episode (Vázquez-Urbez et al., 2011). On the other hand, the Los Bancales build-up (P-2 section) is an 18-20 m thick deposit that extends between the La Requijada and Barranco de los Arcos. The three ages obtained by AR are 233 ± 49 ka (sample MP-A-02), 192.0 ± 26 ka (sample MP-A-01) ka and 148 ± 17 (sample MP-A-05) respectively. Taking into account these ages, the mapping data and the spatial relationships between tufa deposits, it was possible to assert that the Los Bancales tufa deposit and the upper section of the La Requijada build-up were genetically related. The Los Bancales deposit represents other fluvial diffluence episode in this area (Vázquez-Urbez et al., 2011). Finally, downstream of La Requijada, the Ermita de la Blanca build-up (P-7 section) (Fig. 7a) is some 70-80 m thick. The top of this deposit (sample ER-15) yielded a U/Th age of 89.7 ± 0.9 ka.

Other important tufa accumulations have been identified 2-3 km downstream the Monasterio de Piedra, around Nuévalos village (Fig. 3a). In fact the old village is settled on a ~25 m thick tufa build-up (P-10 section). The lower part of this builp-up (Nuévalos Viejo section; Fig. 7a and c) is 254.0 ± 28.8 ka (sample NV-B) and the top could be older than 65.2 ± 24.9 ka (sample NV-A) according AR analysis. A laterally related sample (NG-A) provided a probable AR age older than 130.9 ± 29.0 ka.

In addition to the Pleistocene tufa build-ups several Holocene build-ups, confirmed by ^{14}C ages, have been recognized along the Piedra River valley (Table 3). In the Arco de la Yedra outcrop (P-1 section) (Fig. 7a and b), the sample MP-3, from a peaty level, provided a calibrated age of 2878-2735 years BP. Gastropod shells embedded in moss boundstones (sample MP-2) from the Cola de Caballo (Fig. 7a) deposit provided an age of 933-761 years BP. Downstream in the infilled valley of the Monasterio de Piedra tufa (Piscifactoría; Fig. 7a) deposits have an age of 772-653 years BP (charcoal sample MP-1).

In brief, according to the distribution of the reliable obtained ages, tufa deposits in the River Piedra corresponds to several periods correlated to MIS-9 (340 ka), MIS-7-6, which shows two important pulses (255-230 ka and 145-195 ka) separated by an important erosional event, MIS-5 (80 ka) and, finally, MIS-1 (2.7-0.8 ka BP) (Figs. 7a and 9c).

4.5 Tufas of the river Ebrón valley

In the valley of the River Ebrón, around Castielfabib village, mapping and field work allowed to differentiate tufa deposits corresponding to two encased terraces (Fig. 4a and b). There is a noticeable rupture in the longitudinal profile of the River Ebrón near Castielfabib. Several tufa build-ups were sampled (Fig. 8): Mirador (E-4 section) and Cascada (E-2 section) stratigraphic sections in the upper-older unit, and Convento (E-1 section) and Central (E-3 section) stratigraphic sections, in the lower-younger unit. In the older unit, most common tufa facies are moss boundstones and stromatolites, phytoclastic rudstones and lime mud and carbonate sands. In the younger unit the dominant facies are carbonate sands and silts, but there is also stromatolites, moss and macrophyte boundstones and phytoclastic rudstones.

The Mirador stratigraphic section (M-4 section) is around 77 m thick (Fig. 8a and b). Seven samples were dated by AR (Table 2). The age (152.9 ± 21.3 ka) of the sample MIR-5 has been corrected because the racemization rate of *Candona* genus is slower than *Herpetocypris* genus. Sample MIR-8 shows significant amounts of L-sirina indicating a possible present-day aminoacids contamination. As a consequence the real age would be older than the measured age. Samples MIR-2A and MIR-7 show a similar age (~ 490 ka), older than the whole set of samples. These samples contain *Cyprideis torosa* which indicate waters with high contents in sulphate and chlorine with a wide range of water salinity. That means that sampled tufa deposits are likely inherited from older tufa deposits located upstream and fed by water running across the Upper Triassic evaporites. In addition, two samples correlated with the upper part of the stratigraphic section were dated by U/Th (Table 1). Replicated analyses indicate consistent and reliable ages ranging between 98.3 ka and 100.5 ka (samples MIR B5 and MIR B6). Summarizing, the more reasonable ages point to 186 ka at the bottom, 152 ka in the intermediate stretch and 100 ka in the top of the stratigraphic section.

The Cascada stratigraphic section (E-2 section) (Figs. 4c and 8a) is 20 m in thickness. Four samples from the stratigraphic section (LC-4.4 y LC-B) and from a laterally equivalent deposit (LC-A y LC-B) were dated by AR (Table 2). Samples from the section were corrected in the same way as the sample MIR-5 above. Therefore, the age of this tufa build-up ranges between 150 ka and 98 ka. These ages are supported by U/Th data from a replicate sample (LC-3 A and B) supplying an age of 117.4 ka (Table 1).

The thickness of younger tufa unit exceeds 50 m. The Convento stratigraphic section (E-1 section) (Fig. 8a) (25 m thick) corresponds to the upper section of this unit. Dates obtained by AR in two samples (CON-2 and CON-8) are 10.3 ± 3.1 ka and 16.8 ± 1.8 ka respectively (Table 2). These ages appear reversed respect to the stratigraphic location of samples, however, calibrated ^{14}C ages of three successive samples (CON-1, CON-7 and CON-9) are 6129-5982, 2489 ± 2335 and 2065-1896 years BP respectively (Table 3), which are consistent with their stratigraphic position.

Stratigraphic section Central (E-3 section) (Fig. 8a), located around 1 km downstream of El Convento section, is 25 m thick. In this section AR yielded two ages 19.1 ± 2.5 ka (sample CN-1) and 14.6 ± 1.3 ka (sample CN-5) (Table 2). Nevertheless, younger reliable calibrated ages of 3475-3359 year BP (sample CN-2) and 2961-2787 year BP (CN-4) have been obtained by ^{14}C (Table 3). Comparison of ages by AR and ^{14}C indicates that AR technique does not supply reliable and accurate ages for Holocene times.

In summary, distribution of the reliable ages obtained for the River Ebrón valley evidenced the occurrence of tufa deposition during MIS 6 and 5 (180-100 ka) and MIS 1 (6-2 ka) (Figs. 8a and 9d). Evidence of older tufaceous deposits during MIS 13 (490 ka) should be also taken into consideration.

5. Discussion

Quaternary tufa deposits are widespread along the fluvial network draining the Iberian Ranges (NE Spain). Tufas have been studied in four selected valleys (Añamaza, Mesa, Piedra and Ebrón rivers) arranged in a latitudinal and longitudinal slight gradient. As a rule, tufa build-ups crop out as cut-and-fill and nested terraces. Different fluvial patterns (ramp, ramp wedges, barrage-cascade and associated dammed areas) related to stepped fluvial systems (Arenas-Abad et al., 2010) are recognized. Several techniques (U/Th series dating, Aminoacid Racemization and Radiocarbon) were applied on tufa records to produce a reliable chronological approach well framed in both regional and global paleoclimatological contexts. A general agreement among the different techniques is observed, although U/Th dating provides ages of variable reliability according the features of the geochemistry of tufa systems, and Aminoacid Racemization does not yield accurate ages for Holocene tufa deposits. Anyhow, the ages obtained through the several techniques can be considered as consistent with the geomorphic position of build-ups and the location of samples in stratigraphic sections.

5. 1 Chronological framework of tufa record and paleoclimatic implications

Ages for the Quaternary Iberian Ranges tufa record derived from a multi-technique dating strategy provide a base to decipher favorable conditions for tufa deposition and, therefore, to infer Quaternary palaeoclimatic implications in western Mediterranean areas.

The cumulative probability density function (CPDF), obtained from summed individual probability distributions of the tufa deposits reliable datings (replicates were not considered), reveals several multi-millennial periods of tufa deposition in the studied sector of the Iberian Ranges (Fig. 9e). Firstly, some tufa ages to be confirmed evidence an old period of tufa deposition during MIS-13 (around 490 ka) in the Ebrón River valley. On the other hand, the frequency distribution plot indicates that noticeable periods of tufa accumulation occurred during MIS-10 (345 ka) (with high uncertainty), MIS-9a (284 ka), MIS-7 (206 ka) and MIS-6 (154 ka). Nevertheless, the most active periods of tufa deposition coincide with MIS-5 (85 ka, 105 ka and 120 ka) and MIS-1 (7 ka) respectively (Fig. 9g and h). MIS-3 is poorly represented and the occurrence of MIS-3 tufas in this area remains uncertain. Correspondence between increase in tufa development and interstadials MIS is widely recognized under temperate climates (Henning et al., 1983) but also in the Iberian Peninsula (Martínez-Tudela et al., 1986; Martín-Algarra et al, 2003; Ordoñez et al., 2005; Ortiz et al., 2009; Domínguez-Villar et al., 2011). Some authors accentuate the relevance of humidity during interglacial periods in increasing tufa deposition rates in the Mediterranean region (Martínez-Tudela et al., 1986; Pedley, 2009). First data from speleothem growing stages in NE Iberian Peninsula indicate they are clearly connected to warm climates, with positive hydrological balance and high insolation, during interglacial periods (preferably MIS7, 5 and 1) (Moreno et al., 2013). On the other hand, speleothem growth rates distribution in the NW Iberian Peninsula shows increasing intervals at 200 ka (MIS7), 125 ka, 105 ka and 85 ka (MIS5 e, c and a respectively) and 9-6 ka (MIS1) approximately. In the Iberian Ranges the agreement between these speleothemic stages and the tufa deposition intervals is highly remarkable. However, more surprising is the extensive occurrence of tufa deposition during stadial stages. In fact, tufa formation particularly during MIS-6 in the Iberian Ranges is not uncommon.

At regional scale, preferential accumulation of Quaternary tufa deposits during interglacial periods (Fig. 9g and h) in the Iberian Ranges broadly alternates with the occurrence of glacial and non-carbonate bearing fluvial records in NE Spain (Pyrennes, Ebro Basin and Iberian Ranges) during cold phases (Fig. 9; vertical grey shaded areas) (Fuller et al., 1998; Sancho et al, 2008; Lewis et al., 2009; Benito et al., 2010; García-Ruiz et al., 2013). Lewis et al. (2009) and Benito et al. (2010) recognize extensive fluvial terraces correlated to periods of glacial stability in glaciated headwaters Pyrenean valleys (basins of the Aragón, Gállego and Cinca rivers) at 263 ka, 178-140 ka, 110-97 ka, 68-61 ka, 45-47 ka, 17 ka and 11 ka. It has been established that the glacial system activity and the related fluvial dynamics seem sensitive to insolation controlled by orbital forcing (Lewis et al, 2009). In addition, Fuller et al. (1998) indicate that river aggradation episodes in the Guadalope River valley (Iberian Ranges) occurred at 183-130 ka, 122 ka, 111 ka, 88 ka, 49 ka, 39-36 ka, 24-22 ka, 19-16 ka, 14-12 ka and short Holocene stages. These alluviation phases were controlled by winter storm frequency under stadial periods with prevailing periglacial conditions.

However this broad zipper-like environmental evolutionary model, composed of alternative cold and warm long-term periods shows some inconsistencies. It is truly noticeable the accumulation of tufa records during the Penultimate Glaciation (MIS-6 stage). In NE Iberian Peninsula MIS-6 period is characterized by high water availability in fluvial systems that allows the development of extensive terraces controlled by glacial outwash discharges and/or effective runoff from slopes (Benito et al., 2010) derived from increased seasonal storm frequency (Fuller et al., 1998). At regional scale, the penultimate glaciations (MIS-6) is characterized by an early phase, made of a sequence of warming-cooling events, and a late part with prolonged glacial conditions in western Mediterranean (Martrat et al., 2004) but also in the Portuguese margin (Margari et al., 2014). Stalagmite records from the northern Iberian Peninsula indicate periods of speleothem growth at 149-151 ka (Muñoz-García et al., 2007) and around 175 ka (Stoll et al., 2013), suggesting that growth persisted through the Penultimate Glaciation. In the same way, Wainer et al. (2013) suggest that MIS-6e was relatively warm and humid in south-western France from speleothem record. Wilson et al. (2013) reported increased moisture availability during MIS-6.5 in Greece from lacustrine records. In brief, it seems probed that at lower latitudes favorable conditions (warmer and wetter) during the early MIS6 were enhanced because of the intensification of Asian and African monsoons (Wainer et al., 2013) and related northward deflected North Atlantic polar front (Calvo et al., 2001), in a context of maxima summer insolation (Stoll et al., 2013) and orbital variability (Margari et al., 2014). As a consequence, climate in the Iberian Ranges during the onset of this period would not be as unfavourable as to preclude tufa formation, and the prevailing environmental conditions allowed the formation of significant tufa deposits.

Therefore, it seems that tufa record in the Iberian Peninsula is sensitive to latitudinal shifts of atmospheric fronts and jet streams, as well as perturbations in North Atlantic, due to its location between high and low latitude regions. However, tufa deposition is not sensitive enough to the slight latitudinal and longitudinal gradient at local scale. Differences through time between different fluvial tufa systems located from NW to SE in the Iberian Ranges are not been evidenced. Thus tufa systems response does not record significant changes in environmental conditions (source area and amount of rainfall and/or the vegetation cover) from more continental and Atlantic conditions in the Añamaza River valley to more Mediterranean conditions in the Ebrón River valley.

Insolation is another environmental factor to be considered for driving tufa accumulation. In fact, the cumulative probability density function evidences a close relationship between summer insolation peaks and tufa growth episodes in the Iberian Ranges (Fig. 9f). Under humid climates, summer insolation would favor the increase in temperature, but also in CO_2 production by vegetation and, as a consequence, the CO_2 imput in the karstic system dynamics. In endokarstic environments, Baldini et al. (2005) show a clear relationship between speleothem growth rate and the degree of forest and shrub vegetation coverage. In fact, Stoll et al. (2013) indicate that hiatuses and reductions in stalagmite growth rate occur during extreme minima in summer insolation. The influence of insolation on tufa formation has been also evidenced during the Last Interglaciation in northern hemisphere (Southern Germany) by Frank et al. (2000). The key role of insolation has been also evidenced from seasonal variations of tufa thickness in modern fluvial systems (e.g. Piedra River) (Arenas et al., 2014).

5. 2 Palaeoenvironmental setting

Climate during phases of tufa accumulation in the Iberian Ranges was characterized by prevailing humid conditions producing high groundwater discharges. In addition to water availability, warm temperatures and insolation, seem to reinforce the rates of tufa deposition. The resulting palaeoenvironmental context included the increase in forest vegetation cover, soil CO_2 production, exo- and endokarstic activity and the discharge of chemically active groundwater. This general biostatic context involves the landscape stability, biologically induced (i.e. Goudie et al., 1993; García del Cura et al., 1997). Favourable conditions are intensified particularly during MIS 5, leading to the accumulation of the most important tufa deposits at regional scale, which suggest the wetter and warmer conditions over the last 500 ka in NE Iberia. Similar palaeoenvironmental conditions have been also interpreted at local, regional and continental scales (Henning et al., 1983; Frank et al., 2000; Ordoñez et al., 2005; Dominguez-Villar et al., 2011).

An increase of precipitation over the Mediterranean region under interstadial conditions has been deduced from the Alborán sea record (Moreno et al., 2002) and from growth rates of speleothem in northern Iberian Peninsula (Stoll et al., 2013). In addition, a relationship between warm periods and increased global atmospheric CO_2 concentration has been also observed from ice cores in Antarctica (Indermühle et al., 2000). The increase in atmospheric CO_2 favoured the increase in forest biomass (Higgins and Scheiter, 2012). Thus, higher temperature, precipitation and atmospheric CO_2 concentration favour the soil-vegetation productivity. Therefore, warm and humid conditions could favour a well developed vegetation cover and a high production of soil CO_2. Under these conditions, solution processes were accelerated and, thus, ionic concentrations in groundwater discharges were increased.

In this environmental context, tufa deposition is triggered in the fluvial network when physical CO_2 outgassing is enhanced by the morphological discontinuities in the river longitudinal profiles. High gradient and stepped fluvial systems (*sensu* Arenas et al., 2010) showing different sedimentary architectures (barrage and dammed water areas, prograding-aggrading wedges and high gradient ramps with jumps) resulted in tufa build-ups, according to the local hydrological, geological and morphotopographic context.

On the contrary, during phases of cold conditions (e.g., including wet MIS-4 and arid MIS-2 among others periods; Lewis et al., 2009), deposition of tufa ceased and fluvial incision destroyed partly the previous tufa deposits and favoured the development of a stepped-terraces landscape. Erosion processes in fluvial tufa systems are strongly related to degradation of the vegetation cover on the slopes (Ordoñez et al., 2005) and to increase in detrital supply from mechanical weathering. In addition, the resulting tufa build-ups sometimes include erosional episodes, when the previous tufa build-ups were partially destroyed. These episodes are probably related to short stages of environmental deterioration, including an increase of extreme hydrological events. These erosive events, related to extreme water discharges, are common in present-day fluvial tufa systems, controlling the development of tufa deposits (Vázquez-Urbez et al., 2010).

6 Conclusions

Chronological advances on tufa record in a wide sector of the Iberian Ranges, based on a multi-technique strategy, allow us to advance in the proposal of a regional palaeoclimatic framework, composed of sequential warm and wet long-term stages during the last 500 ka. The following conclusions can be highlighted:

- Chronological data were obtained from Aminoacid Racemization, U/Th disequilibrium series and Radiocarbon. A high consistency was observed among the dating methods, supported by geomorphic and stratigraphic field relations, even though Racemization appears inaccurate for Holocene times.

- The regional tufaceous sequence includes periods of active tufa deposition at 345 ka (MIS-10), 284 ka (MIS-9a), 206 ka (MIS-7), 154 ka (MIS-6), 85 ka (~MIS-5a), 105 ka (MIS-5c), 120 ka (MIS-5e) and 7 ka (MIS-1). Major tufa growth stages occur during MIS-5 and MIS-1 indicating warmer and wetter conditions than today.

- In addition to tufa deposition during interstadials stages, it is remarkable the occurrence of high tufaceos dynamics during MIS-6, indicating that climate in Iberian Peninsula for some time (probably at the onset) of the Penultimate Glacial stage was not so unfavorable to tufa deposition.

- The tufa systems dynamics in NE Iberia over last 500 ka seems sensitive to summer solar forcing, as well as to precipitation regime in the western Mediterranean area, affected by latitudinal shifts of North Atlantic perturbations.

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Figure captions

Figure 1. Location of the studied areas (valleys of the Añamaza, Mesa, Piedra and Ebrón rivers) in the Iberian Ranges (NE Iberian Peninsula).

Figure 2. Añamaza valley area. A) Geological map, with location of stratigraphic sections and other studied sites. B) Field view of a wedge-shaped tufa deposit (Salto

del Cajo), with indication of the stratigraphic sections (A-5, A-7 and A-8) shown in figure 5. C) Detail of section A-10 (metre 2-4), consisting of dominant carbonate sand and silt.

Figure 3. Mesa and Piedra valley areas. A) Geological map, with location of stratigraphic sections and other studied sites. B) Field view of tufa deposits (Los Villarejos N; M-4 secion) in the Mesa Valley. Thick carbonate sand and silt deposits that grade eastward to moss and hanging-stem boundstones. C) Field view of tufa deposit (La Requijada) in the Piedra valley, with indication of the stratigraphic sections (P-3, P-4 and P-5) shown in figure 7. Note the angular unconformity of the Quaternary deposits over Tertiary and Cretaceous rocks. The two main deposition stages are depicted in the Quaternary.

Figure 4. Ebrón valley area. A) Geological map, with location of stratigraphic sections and other studied sites. B) Field view of the valley, showing the two main Quaternary deposition stages arranged in an encased terrace sequence. The locality is Castielfabib. C) Detail of a moss boundstone from section E-2 (Cascada).

Figure 5. A) Stratigraphic sections of the Añamaza valley and their correlation. Note position of samples used for dating and correspondence to MIS. Only samples that yielded reliable dates are indicated. Location of sections in figure 2. B) Field view of the lower half of stratigraphic section A-5 (Salto del Cajo).

Figure 6. A) Stratigraphic sections of the Mesa valley and their relative position. Note position of samples used for dating and correspondence to MIS. Only samples that yielded reliable dates are indicated. Location of sections in Figure 3. B) Field view of the lower part of stratigraphic section M-3 (Jesús Nazareno Este), with abundant stromatolite deposits.

Figure 7. A) Stratigraphic sections of the Piedra valley and their correlation. Note position of samples used for dating and correspondence to MIS. Only samples that yielded reliable dates are indicated. Location of sections in figure 3. B) Field view of stratigraphic section P-1 (Arco de la Yedra). Note the presence of dark grey organic-

matter rich horizons between bioclastic and phytoclastic sands and limestones. C) Field view of the middle part of stratigraphic section P-10 (Nuévalos).

Figure 8. A) Stratigraphic sections of the Ebrón valley and their relative position. Note position of samples used for dating and correspondence to MIS. Only samples that yielded reliable dates are indicated. Location of sections in figure 4. B) Field view of stratigraphic section E-4 (Mirador) (approximately, metres 15 to 65).

Figure 9. Temporal distribution of tufa deposits in the Añamaza (diamonds) (a), Mesa (triangles) (b), Piedra (squares) (c) and Ebrón (circles) (d) valleys. Blue, red and green color symbols refer to U/Th series, racemization and radiocarbon data, respectively. Cumulative probability density function plot of dates (e). Relationships to other palaeoenvironmental records: summer insolation at 42 ºN (Berger and Loutre, 1991) (f), marine isotope stages (MIS) compilation (Bradley, 1999) (g) and SPECMAP isotope curve (Martinson et al., 1987) (h). Vertical grey shaded areas show main stream terrace regional aggradation periods.

Table captions

Table 1. U/Th disequilibrium series data and ages.

Table 2. Aspartic acid and glutamic acid racemization ratios data and ages. Tufa facies samples are always carbonate sands and silts.

Table 3. Radiocarbon data and ages.