Highlights

- New stratigraphic and palaeobotanical study applied to Early-Mid Holocene fluvial tufa deposits.
- Local vegetation was dominated by meso-thermophilous flora whereas in the high-altitudes pinewoods and montane broadleaved communities widespread.
- Charcoal data reveal the local presence of *Taxus baccata* and *Castanea sativa* during pre-Roman times.
- Tufa build-ups correlate with the regional hydrological records evidencing the establishment of humid and thermal climate constrains in Mediterranean continental environments.

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Abstract

Fluvial tufa sections located in the Queiles and Val River valleys (Moncayo Natural Park, Iberian Range, NE Iberia) are investigated following stratigraphic studies, radiocarbon dating and detailed palynological and anthracological analyses, in order to feature vegetation and paleoclimate evolution and discuss with regional results. The studied deposits have been chronologically framed within the Early-Mid Holocene (ca. 9500 to 4000 cal yr BP) in agreement with regional tufa build-up. Climatic and palaeoenvironmental conditions reconstructed for this period fit regional data from lacustrine sequences. The obtained pollen profiles and charcoal results show the existence of a local riparian woodland, where diverse mesophytes, such as deciduous *Quercus*, *Corylus*, *Salix*, *Populus*, *Ulmus*, *Juglans* and *Hedera*, define the main vegetation features in both river valleys. Unexpectedly, both pollen and anthracological data also place *Taxus baccata* and *Castanea sativa* populations growing near the study area, and denoting, in the case of chestnut, its native and long-term presence in the Iberian range. Deciduous (*Quercus faginea/pyrenaica* type) and evergreen oaks (*Q. ilex/coccifera* type) were the main spread regional forests which conformed the meso-mediterranean vegetation belt of the Moncayo Massif and borderlands, accompanied by many warm-loving shrubs like *Olea*, *Phillyrea*, *Rhamnus* and *Pistacia*, pointing out the optimal thermal period of the Holocene. Pinewoods (*Pinus nigra/sylvestris* type) and montane broadleaved communities (*Betula*, *Fagus*) were usually confined to high-altitude elevations following regional palynological sequences data, but charcoal record in our results also addresses its local presence. The findings show that combination of pollen assemblages and detailed charcoal analyses, together with the accurate dating of tufa build-ups, represent an essential tool to complete the regional palaeoclimatic and palaeohydrological reconstructions, as well as to draw precisely the past distribution of unusual taxa.

Palaeobotanical insights from Early-Mid Holocene fluvial tufas in the Moncayo Natural Park (Iberian Range, NE Spain): regional correlations and biogeographic implications

Josu Aranbarri (1, 2, 3*), Miguel Bartolomé (1, 4), Marta Alcolea (5), Carlos Sancho (4), Alessandra Celant (2), Penélope González-Sampériz (1), Concha Arenas (4), Donatella Magri (2), Julio Rodríguez-Lázaro (3)

(1) Instituto Pirenaico de Ecología-CSIC, Avda. Montañana 1005, 50059 Zaragoza, Spain.
aranbarri.josu@gmail.com; mbart@ipe.csic.es; pgonzal@ipe.csic.es

(2) Dipartimento di Biologia Ambientale, Sapienza Università di Roma, Piazzale Aldo Moro, 5, 00185 Rome, Italy. josu.aranbarri@uniroma1.it; alessandra.celant@uniroma1.it; donatella.magri@uniroma1.it

(3) Departamento de Estratigrafía y Paleontología, Universidad del País Vasco-Euskal Herriko Unibertsitatea, B. Sarriena s/n, Ap. 644, 48080 Bilbao, Spain. julio.rodriguez@ehu.es

(4) Departamento de Ciencias de la Tierra, Universidad de Zaragoza, Pedro Cerbuna 12, 50009 Zaragoza, Spain. csancho@unizar.es; carenas@unizar.es

(5) Departamento de Ciencias de la Antigüedad, Universidad de Zaragoza, Pedro Cerbuna 12, 50009 Zaragoza, Spain. malcolea@unizar.es

Abstract

Fluvial tufa sections located in the Queiles and Val River valleys (Moncayo Natural Park, Iberian Range, NE Iberia) are investigated following stratigraphic studies, radiocarbon dating and detailed palynological and anthracological analyses, in order to feature vegetation and paleoclimate evolution and discuss with regional results. The studied deposits have been chronologically framed within the Early-Mid Holocene (ca. 9500 to 4000 cal yr BP) in agreement with regional tufa build-up. Climatic and palaeoenvironmental conditions reconstructed for this period fit regional data from lacustrine sequences. The obtained pollen profiles and charcoal results show the existence of a local riparian woodland, where diverse mesophytes, such as deciduous *Quercus*, *Corylus*, *Salix*, *Populus*, *Ulmus*, *Juglans* and *Hedera*, define the main vegetation features in both river valleys. Unexpectedly, both pollen and anthracological data also place *Taxus baccata* and *Castanea sativa* populations growing near the study area, and denoting, in the case of chestnut, its native and long-term presence in the Iberian range. Deciduous (*Quercus faginea/pyrenaica* type) and evergreen oaks (*Q. ilex/coccifera* type) were the main spread regional forests which conformed the meso-mediterranean vegetation belt of the Moncayo Massif and borderlands, accompanied by many warm-loving shrubs like *Olea*, *Phillyrea*, *Rhamnus* and *Pistacia*, pointing out the optimal thermal period of the Holocene. Pinewoods (*Pinus nigra/sylvestris* type) and montane broadleaved communities (*Betula*, *Fagus*) were usually confined to high-altitude elevations following regional palynological sequences data, but charcoal record in our results also addresses its local presence. The findings show that combination of pollen assemblages and detailed charcoal analyses, together with the accurate dating of tufa build-ups, represent an essential tool to complete the regional palaeoclimatic and palaeohydrological reconstructions, as well as to draw precisely the past distribution of unusual taxa.

Key words: Fluvial tufa, Palynology, Anthracology, Historical biogeography, *Taxus baccata*, *Castanea sativa*

1. Introduction

Fluvial tufa deposits (Pedley, 1990; Ford and Pedley, 1996) have provided to be excellent palaeobotanical archives (Dabkowski, 2014). Charcoal remains and detailed leaf imprints preserved in fluvial tufa sequences constitute extraordinary proxies to develop Quaternary palaeoenvironmental studies (Pentecost, 2005) and to disentangle biogeographic aspects, regarding past distributions of vascular taxa (Ollivier et al., 2011). Examples of broader extension of European endangered or extinct taxa have been successfully derived from many locations across the Mediterranean Basin providing unequivocal, local evidence of key elements like, for example, *Zelkova* (Follieri et al., 1986), nowadays confined to the easternmost Caucasian region (Kvavadze and Connor, 2005). In addition, some works have also evidenced the potential of macrofloral and anthracological remains as direct proxies to infer treeline dynamics (Ali et al., 2003; Di Pasquale et al., 2014) or to identify the autochthony of conflictive tree species (e.g., *Populus alba*, Roiron et., 2004, *Platanus orientalis*, Rosati et al., 2015).

In contrast, tufa palynology has been poorly developed as a research line because of recurrent taphonomic biases that concur in relatively low pollen concentrations (Ricci et al., 2014). Recently, Bertini et al. (2014) concluded that high precipitation rates in tufa formation and depositional system typologies explain the pollen preservation in tufa environments *per se* excluding the general assumption that alkaline environments are responsible for corrosion phenomena. Despite high amount of sterile layers and pollen preservation issues, it has been proved successfully that pollen analysis reflects both local and regional vegetation and, therefore, may represent the climate scenarios when the tufa deposition took place (Taylor et al., 1998). Locally confined pollen assemblages coupled with independent indicators, such as molluscan faunas or isotope geochemistry analyses, have demonstrated to be excellent indicators of past local hydrological oscillations (Vermoere et al., 1999; Murton et al., 2001) that provide further evidence of the sedimentary processes involved, as pollen deposition is mostly related to waterborne transport in tufa depositional environments (Bertini et al., 2014).

In the Iberian Peninsula, vegetation reconstructions focused on pollen analysis of carbonate sequences have scarcely been reported, although some sequences provided successful results spanning palaeobotanically poorly-known time intervals (examples in

González-Sampériz et al., 2010). This is especially evident for Middle and Upper Pleistocene records obtained from rock shelters and caves (e.g., García-Antón and Sainz-Ollero, 1991; Burjachs and Julià, 1994; Schulte et al., 2008), in which pollen-biased studies have been mandatory to disentangle main climate features and to establish broad-scale biostratigraphic correlations (González-Sampériz et al., 2010). Leaf imprints have testified the local evidence of meso-thermophilous taxa like *Quercus faginea, Acer opalus, Alnus glutinosa* or *Corylus avellana* (Martinez Tudela et al., 1986), evidencing the establishment of humid conditions and the spread of broadleaved woodland in the Mediterranean Iberia during the last interglacial. During the Mid Holocene, palynological studies in fluvial travertine sections and barrage systems have also been reported, completing the fragmentary vegetation picture of Iberian continental environments (Taylor et al., 1998). Detailed macrofloral and charcoal studies have been addressed to past distribution of tree species (Menéndez Amor, 1970; García-Amorena et al., 2011; Roiron et al., 2013), in all cases improving the taxonomic and spatial resolution of pollen analysis.

The main goal of this research is to decipher the palaeoenvironmental evolution of the tufa deposits in the valleys of the Queiles and Val rivers during the Early-Mid Holocene by means of detailed analysis of pollen and charcoal assemblages. The vegetation dynamics of the Moncayo Natural Park, hot spot of biodiversity located in the northern sector of the Iberian Range, has been scarcely investigated and previous pollen studies have been focused on mountain environments where ombrotrophic peatbogs and lakes widely dominate (Peñalba, 1994; Sánchez Goñi and Shannon, 1999; Gil-García et al., 2002; Ruiz-Zapata et al., 2002, 2015, among others). Mid- and low-altitude environments have been poorly studied in the area and nearby regions because of the lack of continuous sedimentary records (González-Sampériz, 2004; González-Sampériz et al., 2008). The results shown in this paper complement the palaeobotanical knowledge of the Iberian Range phytogeography. Specific aims are: 1) to define the vegetation history both at a local and a regional-scale by means of detailed and chronologically well-constrained pollen and charcoal profiles; 2) to correlate the main vegetation development of the Early-Mid Holocene time-interval in the Iberian Range, and; 3) to discuss the specific plant traits with special emphasis on past biogeographies.

2. Site description

The studied tufa deposits are located along the valleys of the Queiles and Val rivers, in the northeastern sector of Iberian Range and the adjacent Ebro Depression (Figure 1B). The watershed of the Queiles River is around 550 km^2, with an altitude ranging between 2326 m a.s.l (Moncayo summit) and 250 m a.s.l (mouth at Tudela). It is drained by the Queiles River and its tributary Val River, which flows into the Ebro River (Figure 1C). Both rivers are fed mainly from the karstic aquifer of Araviana-Vozmediano that is hosted mainly in Jurassic limestones surrounding the northern side of the Permian and Triassic Moncayo Massif materials (Gil-Imaz and Pocoví-Juan, 1994). Main springs are found in Agreda (150 Ls^{-1}) and in Vozmediano (500-800 Ls^{-1}) (García-Gil et al., 2013) (Figure 1C). Groundwater discharges are of bicarbonate-calcium type and constitute the source of present and probably past tufa build-ups distributed along the Queiles and the Val valleys.

The climate particularities of the Moncayo Range are determined by its geographical position and its high elevation with respect to the nearby regions, which can be illustrated as a Eurosiberian island surrounded by the semi-arid Ebro Depression eastwards and the continental Northern Plateau (del Valle and San Roman, 1994). The massif receives important rainfall contribution from Atlantic fronts, resulting in a marked contrast between the northern and southern sides (Figure 2). The climate conditions near the studied tufa build-ups (ca. 700-900 m a.s.l.) are defined by a typical Mediterranean regime, with a seasonal precipitation distribution and a summer dry period, while areas of higher altitudes are characterized by more regular rainfall and lower temperatures (Figure 2).

The modern vegetation of the Moncayo Massif (Figure 2) reflects the combined results of climate, edaphic and historical factors, where both Eurosiberian and Mediterranean communities are well-represented in the altitudinal vegetation zonation (Longares, 2004). The meso-mediterranean vegetation belt up to 1000 m a.s.l. is defined by Mediterranean sclerophyllous woodlands dominated by *Quercus ilex* subsp. *ballota* and *Quercus faginea* communities, along with many xero-thermophilous shrubs such as *Quercus coccifera*, *Rosmarinus officinalis*, *Thymus vulgaris* and *Genista scorpius*. Olive cultivars and Aleppo pine reforestations are spread in the region (Figure 2). In the supra-mediterranean level *sensu* Longares (2004), mixed broadleaved woodland including both acidophilous *Quercus pyrenaica* and *Q. robur*, are mixed with *Sorbus aria*, *S. aucuparia*, *Sambucus racemosa*, *Ilex aquifolium* and *Fagus sylvatica*, the latter one increasingly abundant in the higher sectors, reaching 1600 m a.s.l. (Figure 2). The pine belt (both *Pinus sylvestris* and *P. uncinata*), presumably planted and punctually colonized by beech stands, defines the upper treeline in the Moncayo Massif, progressively reaching the treeless oro- and crioro-mediterranean belts, characterized by a scrubland with *Juniperus communis* subsp. *alpina*, *J. sabina* and *Cytisus balansae* subsp. *europaeus*, patched by a *Festuca aragonensis* grassland (Figure 2) (Longares, 2004).

The Moncayo Massif is considered an interesting hot spot of biodiversity, where many circum-Boreal trees are confined to their southernmost range limit (Gómez García et al., 2003). Among them, sessile oak (*Quercus petraea*), pedunculated oak (*Q. robur*) and beech forest stands are the most relevant species (Martínez del Castillo et al., 2015). Their presence is explained by the recurrent water supply and particular edaphic features (Gómez García et al., 2003).

The local vegetation communities in the surroundings of both Queiles and Val tufa deposits are mainly defined by a dense riparian woodland with abundant *Corylus avellana*, *Fraxinus excelsior*, *Tilia platyphyllos*, *Acer monspessulanum*, *Populus tremula*, *Salix atrocinerea*, *Cornus sanguinea*, *Sambucus nigra* and *Hedera helix*. On carbonate rocky areas, many Mediterranean affinity species and heliophytes are present: *Quercus ilex* subsp. *ballota*, *Q. coccifera*, *Artostaphyllos uva-ursii*, *Crataegus monogyna*, *Rosa canina*, *Rhamnus lycioides*, *R. alaternus*, *Cistus ladanifer*, and *Prunus spinosa*, among others (Figure 2).

3. Material and methods

Geological mapping of tufa outcrops along the Queiles and Val valleys (Figure 1C) was undertaken on an aerial photography base (1:18,000 scale). Detailed geomorphic and stratigraphic field studies of the mapped tufa build-up were carried out. Subsequently, selected stratigraphic sections were described and sampled for palaeobotanical and chronological approaches. Facies study followed the nomenclature by Arenas-Abad et al. (2010).

Samples for pollen analyses were selected in the several stratigraphic sections measured in the tufa build-ups (7 samples in Queiles and 7 samples in Val sections, Figure 3) and then processed in the laboratory (ca. 100 gr) following the standard procedures for carbonate facies (Bertini et al., 2014). Results are expressed as percentages with respect to the terrestrial pollen, excluding hygrophytes, aquatic plants, ferns and algae. Cichorioideae and Brassicaceae have been also excluded from the total pollen sum since in some levels the frequencies were up to > 350%, likely caused by taphonomic biases (Ricci et al., 2014). Pollen identification follows Moore et al. (1991).

Samples of 2-5 kg material were collected for anthracological analysis exactly from the same layers sampled for palynological purposes (Figure 3). A systematic dry sieving was used to recover the charcoal fragments; the coarse fraction and large charcoal fragments were collected with a 5-mm mesh; a 2-mm mesh was used to recover the smaller remains. Charcoal fragments were manually fractured according to the three anatomical planes and observed using a reflected-light microscope. Identification of charcoal is derived via comparisons with reference collections of current charred wood and anatomical wood atlases (Schweingruber, 1990).

A total of 7 charcoal samples (4 from Queiles, 2 from Val-1, 1 and 1 from Val-2) were selected for dating at the AMS Direct Laboratory, Seattle (USA). When possible samples were anatomically identified prior to submission to laboratory following Badal et al. (1994) suggestions. Radiocarbon dates were calibrated with Calib v. 7.02 (Stuiver and Reimer, 1993) using the latest INTCAL13 curve (Reimer et al., 2013).

4. Results

4.1. Stratigraphy

The studied tufa deposits crop out along the bottom of the valleys of the Queiles and Val rivers (Figure 1C). They appear as successive build-ups shaping a cut-and-fill terrace system. The present river longitudinal profiles display some knick-points that coincide with the presence of Holocene tufa build-ups corresponding to small tufa barrages. In general, the Holocene deposits of the two studied cases formed in moderate slope river conditions, with small barrages (bryophyte bounstones, phytoclast rudstones and stromatolites) separated by low-slope free-flowing water areas (oncoid rudstones, phytoclast rudstones and coarse detritals) and ponded water areas (phytoclast rudstones, peaty marls and marls) *sensu* Arenas-Abad et al. 2010.

A build-up (41º50'N; 1º51'W; 854 m a.s.l.) in the valley of the Queiles river located very close to the karstic spring of Vozmediano (Figure 1C) was selected to be studied. The tufa deposits are 10 m thick and crop out continuously along 60 m. This outcrop allowed to describe seven sections (Figure 3A, from A to G). Two stratigraphic stretches can be differentiated in the tufa build-up. The lower one (5 m thick) is mainly made of 1) massive and cross-stratified millimeter- to centimeter-long oncoid rudstones and/or 2) massive and laminated gray marls that contain abundant gastropods and charcoal remnants (Figure 3A).). Decimetre-thick lenticular beds made of gravels and sands sometimes appear interbedded. In contrast, the upper unit is made of phytoclast rudstones, bryophyte boundstones and less abundant oncoid. The calibrated ^{14}C ages of four samples (Queiles-A, B, C and G) are 5825±27, 4995±26, 4135±24 and 4060±27 cal yr BP, respectively (Figure 3A) (Table 1).

In the Val River, the selected tufa build-ups (41º52'N; 1º52'W; 765 m a.s.l.) occupy both sides of the river and reach 9 m in thickness. Three stratigraphic sections have been measured (Figure 3B, from 1 to 3); these mainly consist of phytoclast rudstones, plant boundstones, marls and coarse detritals. The lower and middle stretches of these sections include gray marl deposits, up to 2 m thick, that encompass charcoal remnants Both palynological and anthracological studies have been performed in these levels from the 3 sections (Figure 3B). Two samples from the middle part of stratigraphic section VAL-1 provided ages of 7590±35 and 7180±33 cal yr BP, which is consistent with the stratigraphic order. Other sample from the base of section VAL-2 provided an age of 9540±35 cal yr BP (Figure 3) (Table 1).

4.2 Palynologycal results

The palynological analysis performed in the Queiles and Val tufa deposits resulted in fertile pollen samples, identifying at least 109 palynomorph taxa as a consequence of the exceptional pollen preservation. Overall, all the studied deposits show similar pollen spectra (Figure 4) producing a snapshot of vegetation landscape for the Early-Mid Holocene interval in the region, 9500-4000 cal yr BP.

The mesophyte component attains the highest frequencies among the arboreal taxa: *Corylus* followed by *Fraxinus*, *Populus*, *Salix*, *Ulmus*, *Juglans*, *Castanea*, *Taxus* and *Quercus faginea/pyrenaica* type, reveal a typical riparian woodland assemblage. The pollen spectra are completed by *Tamarix*, *Viburnum*, Ericaceae, *Calluna* and *Hedera*, the latter acquiring remarkable values in Queiles (Figure 4). Rosaceae are well-represented in all the deposits together with many heliophytes (*Genista*, *Cytisus/Ulex* type, *Cistus* and *Helianthemum*) and elements with Mediterranean affinity like evergreen *Quercus*, *Juniperus*, *Pistacia*, *Rhamnus*, *Phillyrea* and *Olea*.

Pollen grains attributed to a montane broadleaved component are traced by the sporadic presence of *Betula* and *Fagus*. *Pinus sylvestris/nigra* type probably is not locally present or at least does not form dense stands, while *Pinus pinaster/halepensis* type is practically absent from the fossil record (Figure 4).

Herbs, reaching >30% in some levels, are well-constrained to the local environment. Poaceae and Labiatae, presumably related to calcareous soils, are continuously present similarly to many cosmopolitan taxa like Cichorioideae, Chenopodiaceae and Fabaceae that are commonly linked to open habitats and environments with active geomorphic processes (Ricci et al., 2014). As there is no evidence of agricultural practices in the nearby areas, this assemblage is better explained by natural disturbances than by the spread of nitrophilous elements and weeds.

Hygrophytes, comprising Cyperaceae, Juncaceae, *Typha latifolia* type, *Typha/Sparganium* type, *Thalictrum/Alisma* type, and *Pedicularis* together with many hydrophytes like *Myriophyllum alterniflorum* type, *Potamogeton*, *Nymphaea*, *Nuphar*, *Callitriche*, and *Lemna* are an important component of the vegetation, linked to the type of deposit and the specific geomorphological setting. The high values of Pteridophytes (monolete and trilete fern spores, *Polypodium* and *Equisetum*), sometimes >30%, are also related to local humid conditions (Figure 4). The good pollen preservation, together with the noticeable values of aquatic taxa and ferns, highlights the establishment of a stable environment favorable to palynomoph preservation. This fact is consistent with the sedimentological features, which point to the development of ponds and barrage tufa systems in both Queiles and Val river valleys (Figure 3).

4.3. Anthracological results

The charcoal assemblage obtained from Queiles and Val tufa deposits reflects the local woody flora composition during the Early-Mid Holocene. All the charcoal fragments probably appear related to natural wildfires, since no archaeological settlements or shelters are known in the surrounding of the deposits and some AMS-dated levels preceded the onset of the Neolithic in the region (Table 1). Overall, 272 charcoals have been analyzed, reporting 16 diverse taxa (Tables 2 and 3). The number of charcoal fragments varied among tufa sites and levels, being Queiles better constrained (n= 239) than the Val deposits (n= 33). As in the pollen results, there are no major changes between sites and the charcoal assemblages are quite similar within the 9540 and 4060 cal yr BP time-interval, although some particular taxa are found in specific levels.

Quercus deciduous and *Corylus avellana*, coupling with the palynological results (Figure 4), are the most common broadleaved taxa together with *Quercus/Castanea*, cf. *Ulmus*, *Acer* and *Salix/Populus*, characterizing a dense and diverse riparian woodland during the Early-Mid Holocene in the Queiles and Val riverbanks (Table 2 and 3). The accurately identified piece of charcoal of *Castanea sativa* was AMS-dated, throwing 4135 cal yr BP (Table 1).

Among conifers, *Pinus sylvestris/nigra* type appears continuously in all the studied deposits, becoming the most abundant taxon. *Taxus baccata* is also recorded in Queiles-G, C and A samples, chronologically occurring at 4495, 4135 and 4060 cal yr BP (Table 2). *Juniperus* is sporadically recovered.

Elements with Mediterranean affinity, like evergreen *Quercus*, *Pistacia,* and Rosaceae Maloideae are also found in some layers, although their presence is considerably low in comparison with the mesophytes or the conifer spectra.

5. Discussion

5.1. Early-Mid Holocene vegetation history of the Queiles and Val tufa systems and its regional significance

The detailed pollen analyses applied to fluvial tufa deposits coupled with anthracological data allow reconstructing both local and regional vegetation traits that inhabited varied environments and inferring background climate and hydrological constrains.

From ca. 9540 to 4060 cal yr BP, the local vegetation landscape in both the Queiles and Val tufa build-up was characterized by a well-developed riparian forest around a pond system associated with fluvial streams (Figure 4) (Table 1). The diversity of the riverside taxa was defined by remarkable frequencies of deciduous *Quercus* and *Corylus* accompanied by *Fraxinus*, *Juglans*, *Ulmus*, *Salix*, *Populus* and *Hedera*, a common assemblage recorded nowadays in the Queiles and Val riverbanks. The assemblage was complemented by the anthracological results, denoting the local presence of *Acer* and *Castanea sativa*, not recorded in high amounts in the palynological results. *Taxus baccata* has been abundantly recorded in the charcoal assemblage (Table 2), but sporadically preserved in the pollen spectra (Figure 4). This fact confirms the low traceability of *Taxus* in the palynological sequence, linked to the reduced content of sporopollenin of the pollen exine, becoming recurrently vulnerable to oxidation processes (Havinga, 1967; Mitchell, 1990). Up to now there is no *Taxus* report in the anthracological literature for the Iberian Range, the pollen diagrams only reveal scattered presences (Peñalba, 1994; Sánchez Goñi and Hannon, 1999) and is lacking from sequences confined to the southern Iberian Range (e.g., Ojos del Tremedal, Stevenson, 2000; Villarquemado palaeolake, Aranbarri et al., 2014). The recently published paper by Uzquiano et al. (2015), dealing with the palaeobiogeography of *Taxus baccata* in Iberia, supports that yew populations reached a wider distribution in northeastern Spain between 8000-4000 cal yr BP, synchronously to the maximum spread of broadleaved communities. After that, populations declined, presumably as a consequence of increased drier conditions that favored the establishment of sclerophyllous woodland. Both pollen and charcoal results from the Queiles and Val profiles reveal yew presence during the Mid Holocene in a region where this taxon is not abundantly recorded at present.

Semi-deciduous and evergreen oaks along with numerous thermophilous trees and shrubs characterized the main vegetation landscape of the meso-mediterranean belt at the Moncayo Massif during the Early-Mid Holocene (Figures 4). According to charcoal data, *Quercus* evergreen was not relevant at a local-scale; but the moderate values recorded in the pollen data (ca. 15%) reflect the regional pollen signal rather than local biases. During the same period, pollen sequences located at a similar altitude in intra-mountain valleys (e.g. Villarquemado palaeolake, Aranbarri et al., 2014) and Iberian Range borderlands (e.g. Navarrés, Carrión and van Geel, 1999; Les Alcusses; Tallón-Armada et al., 2014) exhibit the spread of Mediterranean communities dominated by evergreen oaks and many warm-loving taxa (Figure 5). In fact, remarkable presences of *Olea*, *Phillyrea* and *Cistus*, as well as shrubs like *Buxus*, *Rhamnus* and *Juniperus* have been detected in our results, pointing that some favorable warm enclaves were hosted in the lower belts of the Moncayo Massif during the Early-Mid Holocene in agreement with regional data. The continuous presence of *Pistacia* pollen (Figure 4), also traced in the anthracological results (Table 2), suggests that relatively mild winters and moister summers were common during the Mid Holocene in the region, contrarily to nowadays. Charcoal fragments of both *Pistacia lentiscus* and *P. terebinthus* were continuously reported in the nearby Cabezo de la Cruz settlement (Huerva River valley, central Ebro Depression) during the Bronze and Iron Ages (ca. 2750-2500 cal yr BP, Badal et al., 2013). Although the charcoal preservation in our samples does not allow distinguishing *Pistacia lentiscus* from *P. terebinthus*, modern vegetation surveys revealed both species growing in the Ebro Valley at different altitudes (from 70 to 800 m a.s.l. for *P. lentiscus* and from 400 to 1200 m a.s.l. for *P. terebinthus*: http://floragon.ipe.csic.es/index.php), even spreading northwards and reaching the calcareous coastal sectors of the Basque Country (Loidi et al., 1994). The isolated communities of *P. lentiscus* found in the nearby, favorable thermophilous shelters of the Bardenas Reales of Navarra Natural Park are a clear evidence of a broader distribution of the species during the warmer Holocene stages (e.g. Puy Aguila I, Iriarte, 2001) and of its successive contraction to favorable micro-enclaves during the late Holocene. By contrast, the reduced abundance of *Pinus pinaster/halepensis* type in our pollen profiles, suggest that, differently from nowadays in were the Aleppo pine reforestation has been recently extended (Figure 2), was absent locally during the Early-Mid Holocene and probably confined to the lower areas of the central Ebro Basin, as shown by palaeobotanical data (Alcolea, in press and examples therein) similar to its current distribution (http://floragon.ipe.csic.es/index.php, 80-800 m a.s.l).

The relatively low frequencies of *Pinus* pollen represented in our palynological spectra points to both nearby small patches and a regional presence of montane pinewoods, which together with birch communities would occupied the high-altitudes of the Moncayo Range (Figure 4) similar to the current supra-mediterranean levels (Figure 2). Previous pollen profiles obtained in the Iberian Range from sequences located up to 1600 m a.s.l. namely Quintanar de la Sierra (Peñalba, 1994), Las Pardillas (Sánchez Goñi and Hannon, 1999), Laguna Grande (Ruiz-Zapata et al., 2002), Laguna del Hornillo (Ruiz-Zapata et al., 2015), as well as Orihuela del Tremedal (Stevenson, 2000), recorded pine values up to 60% (Figure 5), suggesting that montane pine communities were close to coring sites. This was especially evident in the case of Las Pardillas where *Pinus* stomas where traced in the fossil record (Figure 5) demonstrating its local presence (Sánchez Goñi and Hannon, 1999). According to the modern pollen surveys performed in the northern Iberian Range (Sánchez Goñi and Hannon, 1999), the highest *Pinus* frequencies (ca. 60-80%) are recorded at 1700-2000 m a.s.l., whereas in the lower elevations (800-1200 m a.s.l.) pine values do not reach <40%, being limited by the typical pollen signature of the montane broadleaved communities (*Corylus*, deciduous *Quercus*, *Fagus*). The moister and warmer climate conditions established for the Mid Holocene in continental Mediterranean Iberia (Morellón et al. 2009; Aranbarri et al., 2014) may have promoted the spread of pinewoods in altitude (Figure 5), between 8000 and 4000 cal yr BP. Nevertheless, more samples retrieved from successions at higher elevations are needed in order to infer treeline oscillations.

Similarly, scattered *Fagus* pollen grains found in the Val tufa building (Figure 4) in a sample dated at 7590 cal yr BP are in agreement with regional data that place first evidences ca. 8200 cal yr BP in Las Pardillas (Sánchez Goñi and Hannon, 1999) or at ca. 8600 cal yr BP in Hoyos de Iregua (Gil-García et al., 2002). However, *Fagus* showed sporadic occurrences since ca. 20000 cal yr BP in Laguna Grande (Ruiz-Zapata et al., 2002), even expanding during the Lateglacial, and thus, suggesting the potential of the Iberian Range as a phytodiversity reservoir (Magri et al., 2006; López-Merino et al., 2008; González-Sampériz et al., 2010).

The general humid and warm conditions inferred by the pollen profiles from both Queiles and Val tufa build-ups between ca. 9500-4000 cal yr BP were also defined at a broader-scale by many sedimentological, geochemical and geomorphological proxies allowing to perform interesting palaeohydrological correlations for the inner Iberian Mediterranean realm. The tufa deposition in the Val tufa build-up started at 9540 cal yr BP and continued until ca. 4060 in Queiles deposit (Figure 3) (Table 1), corresponding regionally to the maximum accumulation of the Holocene tufa systems in the Iberian Range (Sancho et al., 2015). This was particularly well-recorded during the Early to Mid Holocene, when tufa build-ups occurred in the nearby Añamaza Valley (Arenas et al., 2014), Guadalaviar River (Sancho et al., 1997), Mijares River (Peña et al., 2000) or in Trabaque Canyon (Domínguez-Villar et al., 2012). In the Upper Ebro Depression, the tufa growing stages in Purón and Molinar rivers began at 9275 and 7860 cal yr BP respectively, and continued until ca. 4000 cal yr BP, synchronous to the regional establishment of mixed broadleaved woodland (González-Amuchastegui and Serrano, 2015). Moister conditions and higher water availability resulting in the highest Holocene lake-levels were also inferred from nearby lacustrine records like, Estanya Lake (Morellón, et al., 2009), Marcelino palaeolake (Pellicer, et al., 2016) or Conquezuela basin (Aranbarri et al., 2015). The geochemical signatures obtained from the sediments of both lakes reflected a massive carbonate deposition, likely due to increased temperature between 7500 and 5000 cal yr BP. In the Bardenas Reales Natural Park, a humid phase at ca. 4790 cal yr BP inferred by the occurrence of aquatic and marsh gastropod assemblages in alluvial records (Sancho et al., 2008; Murelaga et al., 2012) matches the rise in hygrophilous trees (*Alnus*, *Corylus*) and ferns (e.g. Puy Aguilar I settlement, Iriarte, 2009) nowadays absent in the region.

Definitively, the vegetation reconstruction and the hydrological features defined in both Queiles and Val fluvial tufa systems (Figure 3) are well-encompassed in the climate background of the inner Mediterranean Iberia. The lagged onset of humid conditions in the continental setting comparing to northern areas, were presumably the consequence of the divergence of the Atlantic fronts (Benito et al., 2003), coupled with the continental behavior of the study site that is characterized, even at present, by high evapotranspiration rates at both diurnal and annual scales. The lack or decrease of tufa deposits during the Early Holocene in the previously mentioned river valleys is consistent with many well-dated, multiproxy-based records from continental

Mediterranean environments (e.g., Villarquemado palaeolake, Aranbarri et al., 2014, lake Estanya, Morellón et al., 2009; González-Sampériz et al., under review or Salines playa lake, Burjachs et al., in press) that show a parkland-like landscape with reduced lake levels until ca. 9000 cal yr BP. Similarly, the reduced, almost absence of tufa deposits in the Queiles build-up during the Late Holocene, ca. 4060 cal yr BP, (Figure 3), reflects a clear geomorphic adjustment to the establishment of drier climate conditions, well-represented during the last 4000 years at the Iberian-scale (Martín-Puertas et al., 2008; Arenas et al., 2014). The significant reduction of tufa development during the last 2000 cal yr BP in the Iberian Range coincides with a decrease in summer insolation as well as lower water availability (Rico-Herrero et al., 2013). Anyway, in some particular settings, human impact on water resources and land use may have also altered adversely both vegetation landscape (Carión et al., 2010) and the tufa accumulation processes, mainly during the Eneolithic, Bronze and Iron Age periods at regional (González-Amuchastegui and Serrano, 2015) but also at European scale (Goudie et al., 1993).

5.2. New insights about the pre-Roman presence of *Castanea sativa* in the Iberian Range

The origin of *Castanea sativa* populations in the Iberian Peninsula has aroused controversy, as its presence was mostly related to its introduction during the Roman times (Laguna Lumbreras, 1997). During the 80s, most published works used Castanea pollen as criteria to establish the onset of a landscape transformation by changes in the economic production modalities and the consequent spread of arboricultural practices (Tornqvist et al., 1989). Some of these works, however, have poor chronological control. Palaeobotanical works were not even considered as an evidence of a possible autochthony of chestnut in the studied regions (e.g., Sánchez Goñi, 1988). In more recent times, the incorporation of molecular techniques and detailed radiocarbon-based palaeoenvironmental reconstructions brought new evidences of chestnut distribution across the Mediterranean Basin (Fineschi et al., 2000; Conedera et al., 2004), discussing possible refugia areas and postglacial colonization routes. Nevertheless, the presence of *Castanea sativa* during the Holocene at Iberian-scale has not been accurately mapped and new data have been scarcely reported, especially concerning the macrofossil record.

Using an extensive palynological approach, Krebs et al. (2004) confirmed that *Castanea sativa* populations were confined to the Cantabrian coastal humid sectors during the Last Glacial Maximum. Anthracological data evidenced that chestnut was a significant taxon together with many deciduous trees like *Betula*, deciduous *Quercus*, *Sorbus aria*, and *Corylus avellana* in Cueva del Conde between ca. 42400 and 36500 cal yr BP (Uzquiano et al., 2008), at La Pila at ca. 14000 cal yr BP (Uzquiano, 1992, 2014) or Altamira at ca. 19220 cal yr BP (Uzquiano, 2014), thus contradicting traditional assumptions that *Castanea sativa* was extinguished during the last glacial cycle (Fineschi et al., 2000) (Table 4). During the Holocene, pre-Roman macrofossils of *Castanea sativa* were dispersed in the Eurosiberian sector, in many archaeological sites confined to Atlantic coastal humid and warm environments (e.g., Kobeaga II, Iriarte et al., 2007-2008), as well as in mid-altitude elevations, where a mixed broadleaved woodland was widespread, following the implementation of humid climate conditions (e.g. Mendandia, Ruiz-Alonso and Zapata, 2015; Arenaza, Uzquiano and Zapata, 2000; Galician Bronze and Iron Age archaeological settlements, Figueiral and Bettencourt, 2004; Martín-Seijo et al., 2012, in press) (Table 4).

In the Iberian Range, and particularly in the Moncayo Natural Park, *Castanea sativa* is not abundant at present, although some tree stands are found in the watersheds of the Queiles and Val rivers, witness of its past. The high amount of *Castanea/Quercus* charcoal fragments in both Queiles and Val tufa build-ups at 7590 and 4135 cal yr BP, together with an unquestionable *Castanea sativa* charcoal fragment radiocarbon dated at 3770±24 (Table 3), suggest *Castanea sativa* presence in the Moncayo Massif during, at least, the Mid Holocene as part of a dense and diverse riparian environment. This was also evidenced by means of pollen analysis in both Queiles and Val tufa records where chestnut was already found at 9540 cal yr BP (Figures 4 and 6), pointing its presence even during the Early Holocene. The siliceous soils that characterize the Moncayo Massif (Fidalgo and Ibarra, 2000) may have favored the presence of acidophilous species like chestnut, such as it has occurred at present to other species (i.e., pedunculated oak *Quercus robur*, Figure 2).

The impact of the Roman conquest in terms of arboricultural diffusion of “exotic plants” has been widely demonstrated in the central Ebro Depression by means of both pollen (González-Sampériz, 2004) and archaebotanical data (Alonso, 2005).

Commonly, chestnut is traced as an important cultivar together with many other trees, such as *Laurus nobilis*, *Juglans regia* and *Vitis vinifera* (i.e., in the Roman site of La Cabañeta, near Zaragoza-Caesaraugusta, González-Sampériz, 2004), fitting the typical assemblage of the Roman world in the Mediterranean Basin (Conedera et al., 2004; Mercuri et al., 2013). The onset of the Roman culture in the Moncayo Massif borderlands is well demonstrated by the foundation of the rural *municipium* of *Turiaso* (currently Tarazona, 31-28 B.C, Valverde, 2012-2013) which became a strategic and prosperous enclave under the government of Emperor Augustus (García and Pérez, 2011). However, up to now, there is not any archaebotanical findings suggesting the local presence of chestnut orchards until the Middle Ages, with scattered frequencies reported in the high-altitudinal sequences (Figure 6) but never reaching the values acquired in the central Iberian records, where chestnut was one of the most representative arboricultural element (e.g., Lanzahíta sequence, López-Sáez et al., 2010; Peña Negra mire, Abel-Schaad et al., 2012). Then, the scattered presence of *Castanea* pollen in the Iberian Range cannot be exclusively attributed to cultivation. There is no pollen sequence showing an exponential increase in chestnut with respect to the pre-Roman trend. More analyses performed in natural archives like the tufa settings reported in the present paper, are crucial to achieve a better understanding of the naturalness of modern landscapes and to accurately trace the biogeographic traits of key and still controversial origin taxa like *Castanea sativa*.

Our data suggest that *Castanea sativa* is native to the southern Iberian Range and its presence in the riparian environment, even at present, is the consequence of the combination of edaphic, climatic and biogeographic drivers, discarding its introduction in Roman times. *Castanea* communities could have expanded through the Iberian Range following the onset of moist climate conditions, presumably during the Lateglacial and Early Holocene, as shown by the palynological results recorded in Laguna Grande (Ruiz-Zapata et al., 2002), in Laguna del Hornillo (Ruiz-Zapata et al., 2015) or in the Hoyos de Iregua peat section during the Mid and Late Holocene (Gil-García et al., 2002) (Figure 6). Another plausible hypothesis may be the long-term persistence of scattered *Castanea sativa* populations in favorable intra-mountainous shelters or fluvial domains, like Queiles and Val riverbanks, where its long-term prevalence was granted in a local, moist and meso-thermal environmental context. In fact, *Castanea* pollen was reported from many deposits spanning the Last Glacial

Maximum (e.g., Laguna Grande, Ruiz-Zapata et al., 2002) (Figure 6) and highlighting, in all cases, its naturalness in the Iberian Range.

6. Conclusions

The present study fills a palaeobotanical and palaeoclimatic information gap in middle altitudes of the northern flank of the Iberian Range, where the available vegetation traits were only reconstructed by high-altitudinal pollen profiles or by records confined to the southernmost Mediterranean areas. The location of the Range, strategically-placed between the Eurosiberian climatic region and the Mediterranean continental realm, allows some interesting vegetation, climatic and hydrological features to be recognized:

1) Fluvial tufa accumulation started at ca. 9540 in the Val River valley and culminated at ca. 4060 cal yr BP in the Queiles River valley, a period of humid conditions, as reported on a larger scale by regional lacustrine sequences, pointing climate features as the main driver of these geomorphological formations.

2) Pollen and anthracological studies of tufa build-ups have the potential to complete the palaeoclimatic and palaeobotanical information in those regions where natural deposits like lakes and peat bogs are scarce.

3) Both local and regional information inferred from Val and Queiles tufa deposits have addressed:

- Local vegetation was characterized though pollen and charcoal analyses, suggesting a riparian woodland where deciduous *Quercus* together with *Corylus avellana*, *Ulmus*, *Castanea*, *Acer*, *Juglans* and *Hedera* were the main arboreal components. Small, nearby patches of conifers and Mediterranean elements cannot be discarded.
- Pinewoods and birch communities probably dominated in high-altitude environments, whereas the meso-mediterranean belt was defined by a mixed Mediterranean oak woodland with many thermophytes confined to protected areas.

4) *Olea*, *Phillyrea* and *Pistacia* expanded between ca. 9000 to 7000 cal yr BP, as the result of the Early-Mid Holocene thermal optimum in the region.

5) *Taxus baccata* was locally present at least between ca. 5000 and 4000 cal yr BP. The first report of yew in the macrofossil assemblage in the Iberian Range is also highlighted.

6) *Castanea sativa* populations were native to the Moncayo Massif according to both palynological and anthracological data, contrary to the general assumption that they were introduced in the region after the Roman conquest.

In sum, this contribution not only has brought new data related to the palaeoenvironmental features of continental Mediterranean Iberia during the Early and Mid-Holocene, but also has confirmed the potential role of the Iberian Range as a long-term phytodiversity reservoir in the biogeographical history of southern Europe.

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Figures and tablet captions

Figure 1. A and B: Location of the studied areas (Queiles and Val river valleys) in the northern hemisphere and in the Iberian Range (NE Spain). C: Main geological and geomorphological features along with the location of the main tufa build-ups in the studied valleys.

Figure 2. Modern vegetation zonation in the Moncayo Massif (modified from Longares 2004). Main climate features extracted from the *Atlas Climático Digital de Aragón* (Cuadrat et al., 2007), have also been displayed following an altitudinal gradient. Studied tufa build-ups location is shown by a red star.

Figure 3. Stratigraphic characteristics of the tufa build-ups. Nomenclature of facies according to Arenas-Abad et al. (2010). Dates are indicated in cal yr BP (Table 1).

Figure 4. Palynological results from Queiles tufa and the different Val tufa build-ups. Radiocarbon data have also been included in order to show the beginning of tufa accumulation.

Figure 5. Vegetation trends showed by Mid Holocene pollen sequences located in the supra- and meso-mediterranean belts of the Iberian Range. The records cited in the Figure 6 have been also included and follow; 1) Villarquemado palaeolake (Aranbarri et al., 2014); 2) Orihuela del Tremedal (Stevenson, 2000); 3) Somolinos tufa lake (Currás et al., 2012); 4) Laguna del Hornillo (Ruiz-Zapata et al., 2015); 5) Hoyos de Iregua (Gil-García et al., 2002); 6) Laguna Nava (Gil-García et al., 1996); 7) Trampal de Nieva (Gil-García and Ruiz-Zapata, 2004); 8) Quintanar de la Sierra (Peñalba, 1994); 9) Laguna Grande (Ruiz-Zapata et al., 2002); 10) Las Pardillas (Sánchez Goñi and Hannon, 1999); 11) Queiles tufa (present study) and 12) Val tufa deposits (present study).

Figure 6. Presence of *Castanea sativa* pollen during pre- (green) and Roman times (red) in sedimentary records confined to the Iberian Range. The sites location has been displayed in Figure 5.

Table 1. Radiocarbon dates (AMS) for the Queiles and Val tufa buildings obtained from charcoal samples.

Table 2. Anthracological results from Queiles tufa building.

Table 3. Anthracological results from the different Val tufa buildings.

Table 4. Radiocarbon dates of Iberian archaeological sites reporting *Castanea sativa* and *Castanea/Quercus* macrofossils prior to the pre-Roman period. Dates were calibrated by means of Calib v.7.02 software (Stuiver and Reimer, 1992) and chronologically ordered to facilitate readability. *Radiocarbon data directly performed on *Castanea sativa* charcoal. ***Castanea sativa* leaf and wood fragments retrieved from natural deposits.

Lab ID	Samples	Building	Material	Radiocarbon date (^{14}C AMS yr BP)	Age error (yr BP)	Mean calibrated age (cal yr BP)
D-AMS 008305	QUEILES-G	Queiles	Charcoal	3722	27	4060
D-AMS 010099	QUEILES-C	Queiles	*Castanea sativa*	3770	24	4135
D-AMS 010098	QUEILES-B	Queiles	*Salix/Populus*	4416	26	4995
D-AMS 008304	QUEILES-A	Queiles	Charcoal	5044	27	5825
D-AMS 008306	VAL-1 Top	Val-1	Charcoal	6237	33	7180
D-AMS 008307	VAL-1 Base	Val-1	Charcoal	6722	35	7590
D-AMS 013885	VAL-2 Base	Val-2	*Pinus nigra/sylvestris* type	8580	35	9540

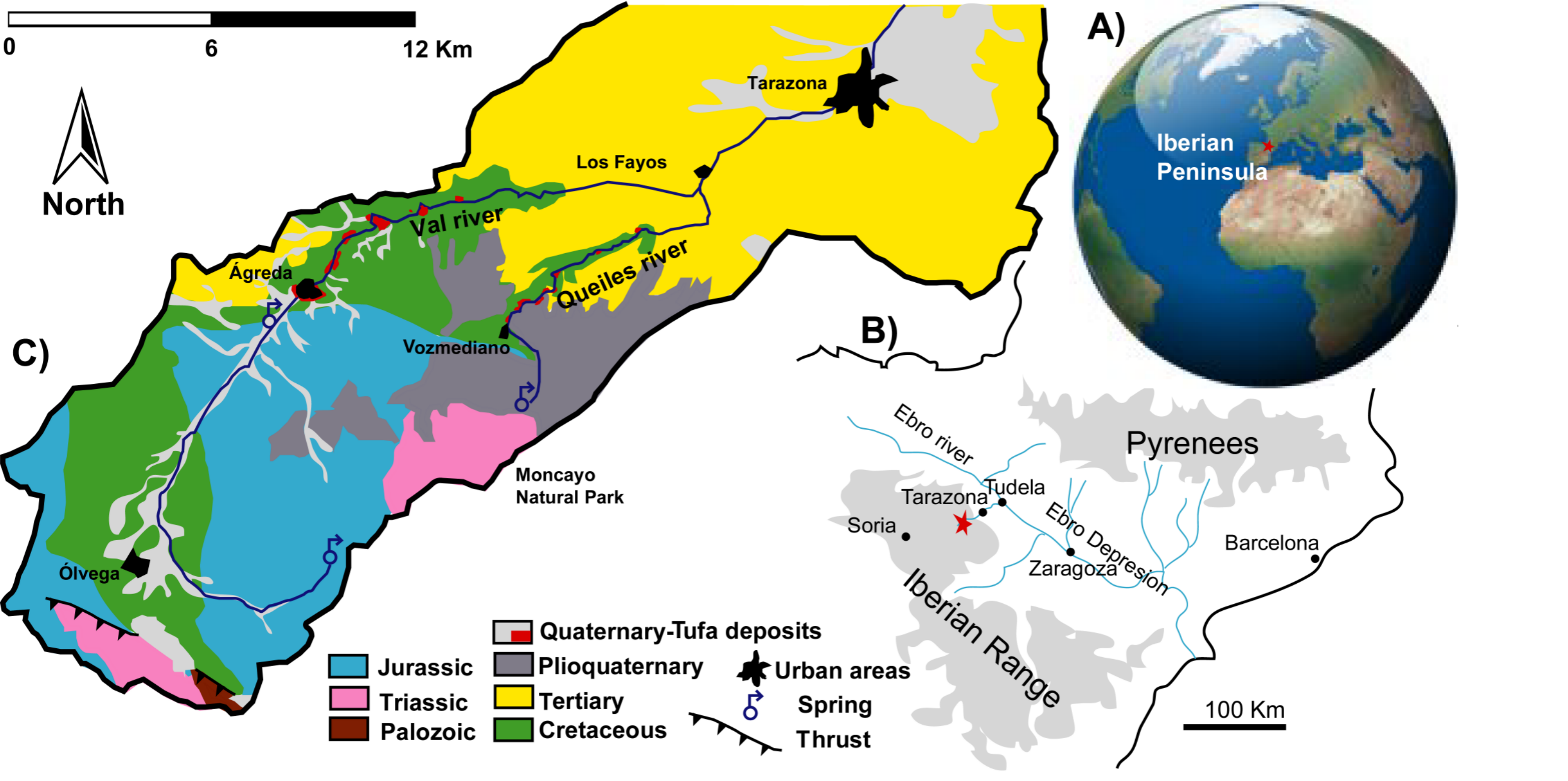
	QUEILES DEPOSIT						
	QUEILES-A	QUEILES-B	QUEILES-C	QUEILES-D	QUEILES-E	QUEILES-F	QUEILES-G
Taxa/^{14}C date	5825 cal yr BP	4995 cal yr BP	4135 cal yr BP				4060 cal yr BP
Acer sp.	1						
Castanea sativa			1				
cf. *Corylus avellana*	6		1				1
cf. *Ulmus*			2				
Juniperus sp.	2	2				1	
Pinus nigra/sylvestris type	51	19	27			1	12
Pistacia sp.	2		1				
Quercus sp.							5
Quercus/Castanea			23				
Quercus deciduous	1	9	28	1			5
Quercus evergreen		1					
Rosaceae Maloideae	1						
Salix/Populus		2					
Taxus baccata		1	23				2
Indeterminable		3			1		
n=	64	37	109	1	1	2	25

	VAL DEPOSITS						
	VAL-1 Top	VAL-1 Base	VAL-2 Top +4m	VAL-2 Top 6 cm	VAL-2 Base	VAL-3 Top 40 cm	VAL-3 Base
Taxa/^{14}C date	7180 cal yr BP	7590 cal yr BP			9540 cal yr BP		
Conifer indetermina		5					
Juniperus sp.		2					
Pinus nigra/sylvestris type	4				11		
Quercus/Castanea		2					
Quercus deciduous	2	3					
Rosaceae Maloideae			1				
Indetermina				1		1	1
n=	6	12	1	1	11	1	1

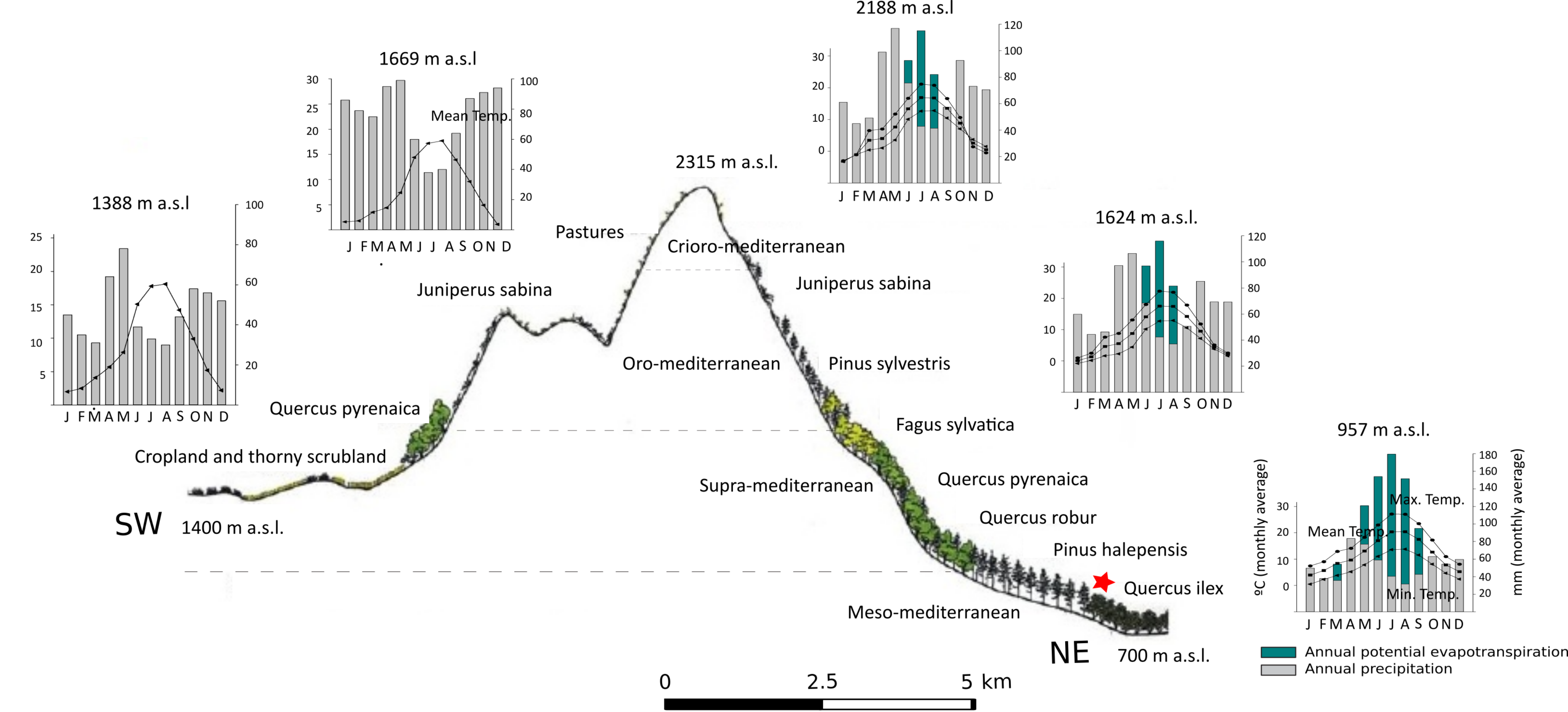
Site	Altitude (m a.s.l.)	Radiocarbon date (^{14}C yr BP)	Mean calibrated age (cal yr BP)	Anthracological assemblage	Reference
Val tufa		6722 ± 35	7590	*Pinus nigra/sylvestris-Juniperus-Quercus* deciduous	Present study
Queiles tufa		3770 ± 24	4135	*Pinus nigra/sylvestris-Quercus* deciduous-*Corylus avellana-Taxus baccata*	Present study
Silvade**		1700 ± 30	1605	*Erica cinerea-vagans*	García-Amorena et al., 2007
Finca Galea**	65	1960 ± 100	1915	*Quercus* subgen. *Quercus* Schwarz	García-Amorena et al., 2008
Pintia	775	2470 ± 30 2640 ± 30	2580 2760	*Pinus Pinaster* Ait.-*Quercus ilex*. L. type-*Quercus faginea* Lam. and *Q. pyrenaica* Wild. type-*Juniperus* spp.-*Pinus* gr. *sylvestris/nigra*	Rubiales et al., 2011; Hernández et al., 2011
Castelo de Matos	890	2700 ± 90 2730 ± 70	2825 2840	Deciduous *Quercus-Corylus avellana-Quercus suber-Pinus sylvestris-Sorbus aucuparia*	Figueiral, 1996
St. Julião	297	2750 ± 60 2840 ± 80	2850 2965	Deciduous *Quercus-Corylus avellana-Ilex aquifolium-Acer sp.-Frangula alnus*	Figueiral, 1996; Figueiral and Bettencourt, 2004
Pego	220	3086 ± 43	3290	*Quercus* deciduous-Fabaceae-Rosaceae/Maloideae-*Corylus avellana*	Martín-Seijo et al., in press
Sola		3338 ± 33 3450 ± 37	3575 3715	*Quercus* deciduous-Fabaceae-*Quercus* sp. evergreen-*Corylus avellana*-Rosaceae/Maloideae	Figueiral and Bettencourt, 2004; Martín-Seijo et al., in press

Arenaza	180	3580 ± 70 3835 ± 55	3880 4250	*Quercus robur/petraea-Q. faginea-Q. ilex-Sorbus aria*	Uzquiano and Zapata, 2000
Santimamiñe	137	3710 ± 40 5010 ± 40 5450 ± 50 7580 ± 50 10100 ± 60 10060 ± 60	4050 5745 6250 8390 11690 11595	*Quercus* subgen. *Quercus*-*Prunus* sp.-*Arbutus unedo*-*Betula* sp.-*Fraxinus* sp.-*Alnus* sp.	Euba Rementeria, 2011
Lamas de Abade	220	3980 ± 40 4090 ± 40	4460 4605	*Quercus* sp. deciduous-*Alnus* sp.-Rosaceae/Maloideae-*Salix* sp./*Populus* sp.	Martín-Seijo et al., 2012
Bitarados		4046±42	4525	*Quercus* deciduous-*Corylus avellana*-Rosaceae/Maloideae-*Quercus* sp. evergreen-Fabaceae	Martín-Seijo et al., 2012
Cova de El Toll		5220 ± 100 5490 ± 100 5800 ± 100	6000 6285 6600	*Buxus sempervirens*-Deciduous *Quercus*-*Acer*-*Quercus ilex*	Allué et al., 2013
Los Canes	325	5865 ± 70	6680	*Pinus sylvstris*-deciduous *Quercus*-*Q. ilex*-*Arbutus unedo*-*Fagus sylvatica*-*Sorbus aria*	Uzquiano, 1992b
Mendandia	720	6540 ± 70	7455	*Pinus*-*Fagus*-*Quercus ilex*-*Q.* subg. *Quercus*-*Acer*	Ruiz-Alonso and Zapata, 2015
Kobeaga II	205	6945 ± 65	7780	*Quercus ilex*-*Q.* subg. *Quercus*-*Corylus avellana*-*Arbutus unedo*	Iriarte et al., 2007-2008
El Espertín	1260	7790 ± 120	8610	*Pinus sylvestris*-deciduous *Quercus*-*Fagus sylvatica*-*Betula*	Uzquiano, 1992b
Peña del Perro	60	9260 ± 110	10450	Deciduous *Quercus*-*Sorbus aria*-*Arbutus unedo*-*Clematis* sp.	Uzquiano, 1992b
Laminak II	90	11380 ± 140 11700 ± 140	13230 13535	*Quercus ilex/suber*-deciduous *Quercus*-*Q. pyrenaica*-*Corylus*	Uzquiano, 1994

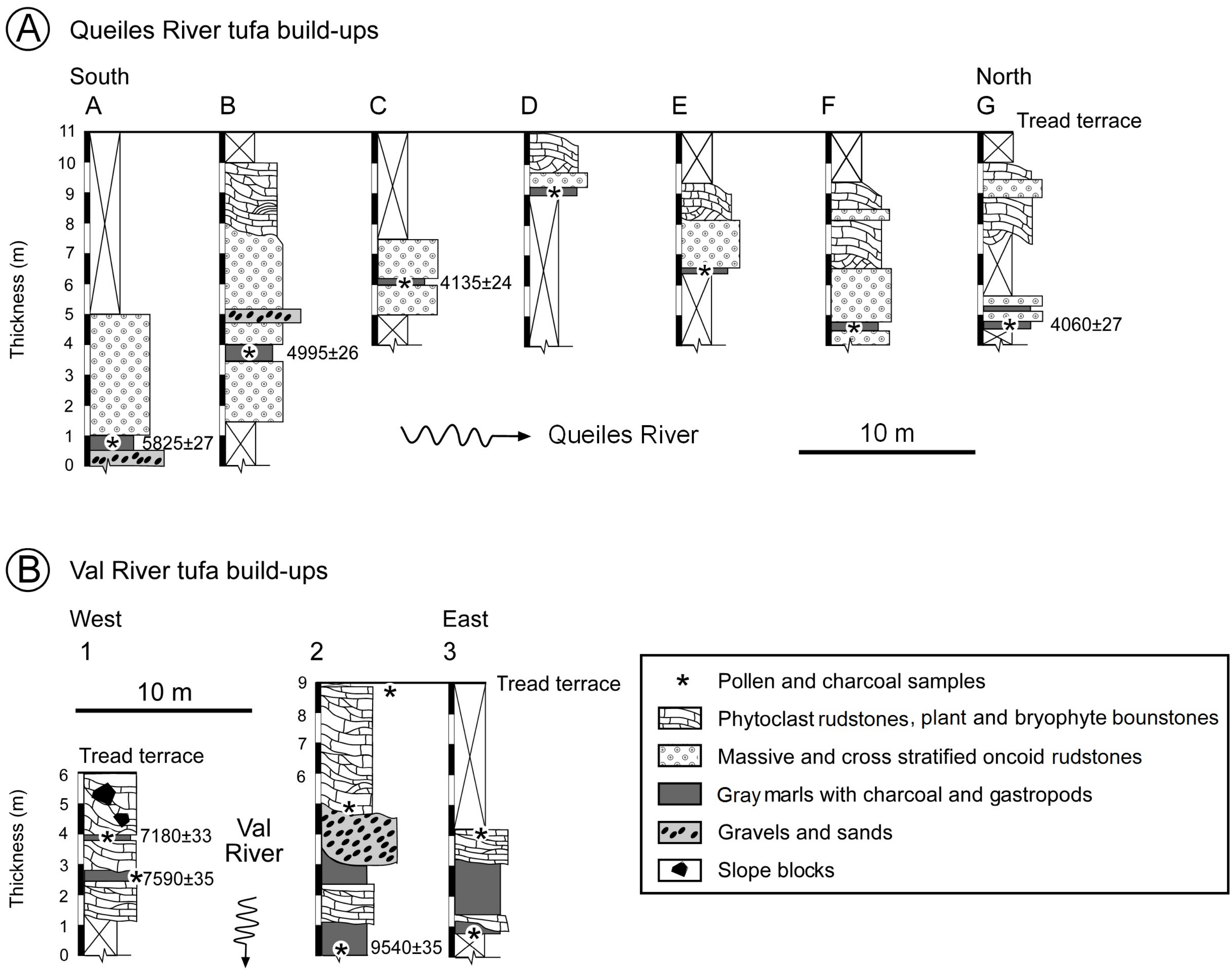
				avellana-Prunus sp.	
La Pila	25	11710 ± 120 12160 ± 130 12580 ± 190	13540 14055 14810	*Juniperus-Betula-Salix-*deciduous *Quercus-Sorbus aria-Cytisus*	Uzquiano, 1992a, 2014
Altamira	75	15919 ± 230	19220	*Juniperus-Salix-Cytisus*	Uzquiano, 2014
Cueva del Conde	180	32530 ± 440 37710 ± 470 38250 ± 390	36540 42040 42385	*Pinus sylvestris-Betula-Sorbus aria-Corylus avellana*	Uzquiano et al., 2008
Cueva de Covalejos	105	30380 ± 250 32840 ± 280 41640 ± 650	34370 36885 45040	*Betula-Pinus sylvestris-Sorbus aria-Quercus robur-Corylus avellana-Hippophae rhamnoides*	Uzquiano 2005



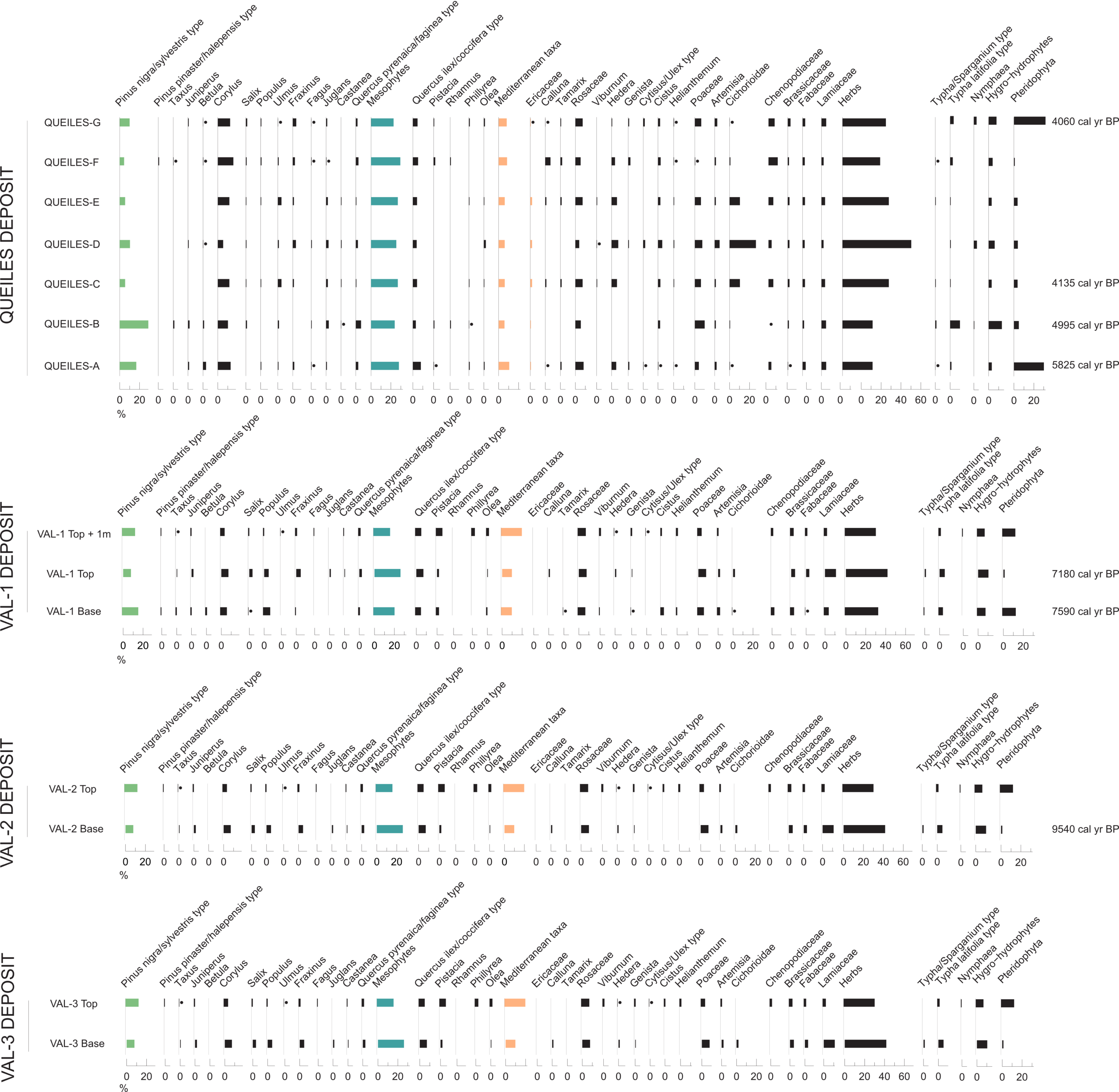
0
6
12 Km
North
A)
Iberian
Peninsula
B)
Ebro river
Pyrenees
Tudela
Tarazona
Soria
Ebro Depresion
Zaragoza
Barcelona
Iberian Range
100 Km
C)
Tarazona
Los Fayos
Val river
Queiles river
Ágreda
Vozmediano
Moncayo
Natural Park
Ólvega
Jurassic
Triassic
Palozoic
Quaternary-Tufa deposits
Plioquaternary
Tertiary
Cretaceous
Urban areas
Spring
Thrust



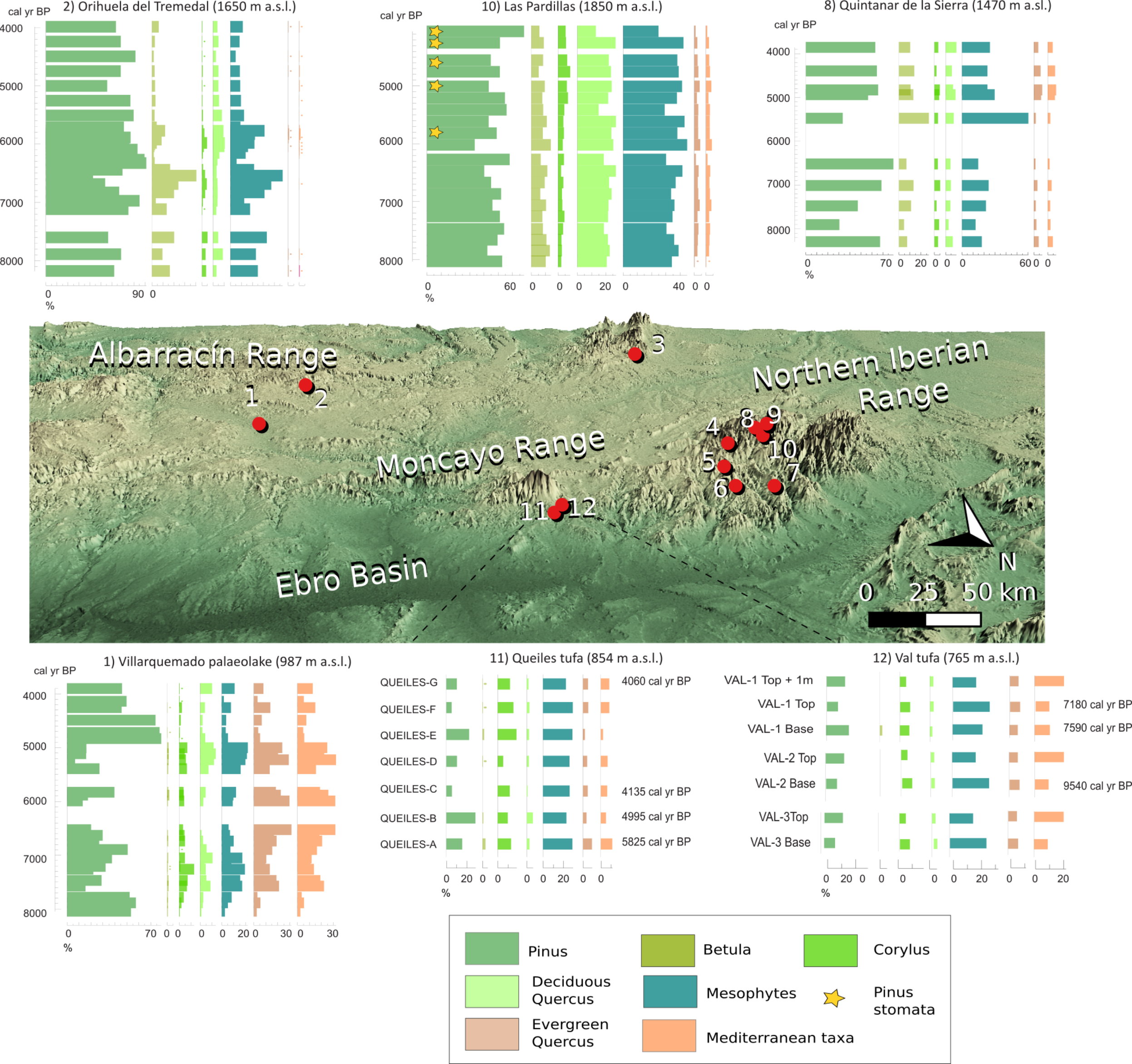
1388 m a.s.l
1669 m a.s.l
Mean Temp.
2315 m a.s.l.
2188 m a.s.l
1624 m a.s.l.
957 m a.s.l.
Pastures
Crioro-mediterranean
Juniperus sabina
Juniperus sabina
Oro-mediterranean
Pinus sylvestris
Quercus pyrenaica
Fagus sylvatica
Cropland and thorny scrubland
Supra-mediterranean
Quercus pyrenaica
Quercus robur
Pinus halepensis
Quercus ilex
Meso-mediterranean
SW
1400 m a.s.l.
NE
700 m a.s.l.
0
2.5
5 km
Max. Temp.
Mean Temp.
Min. Temp.
ºC (monthly average)
mm (monthly average)
J F M A M J J A S O N D
Annual potential evapotranspiration
Annual precipitation



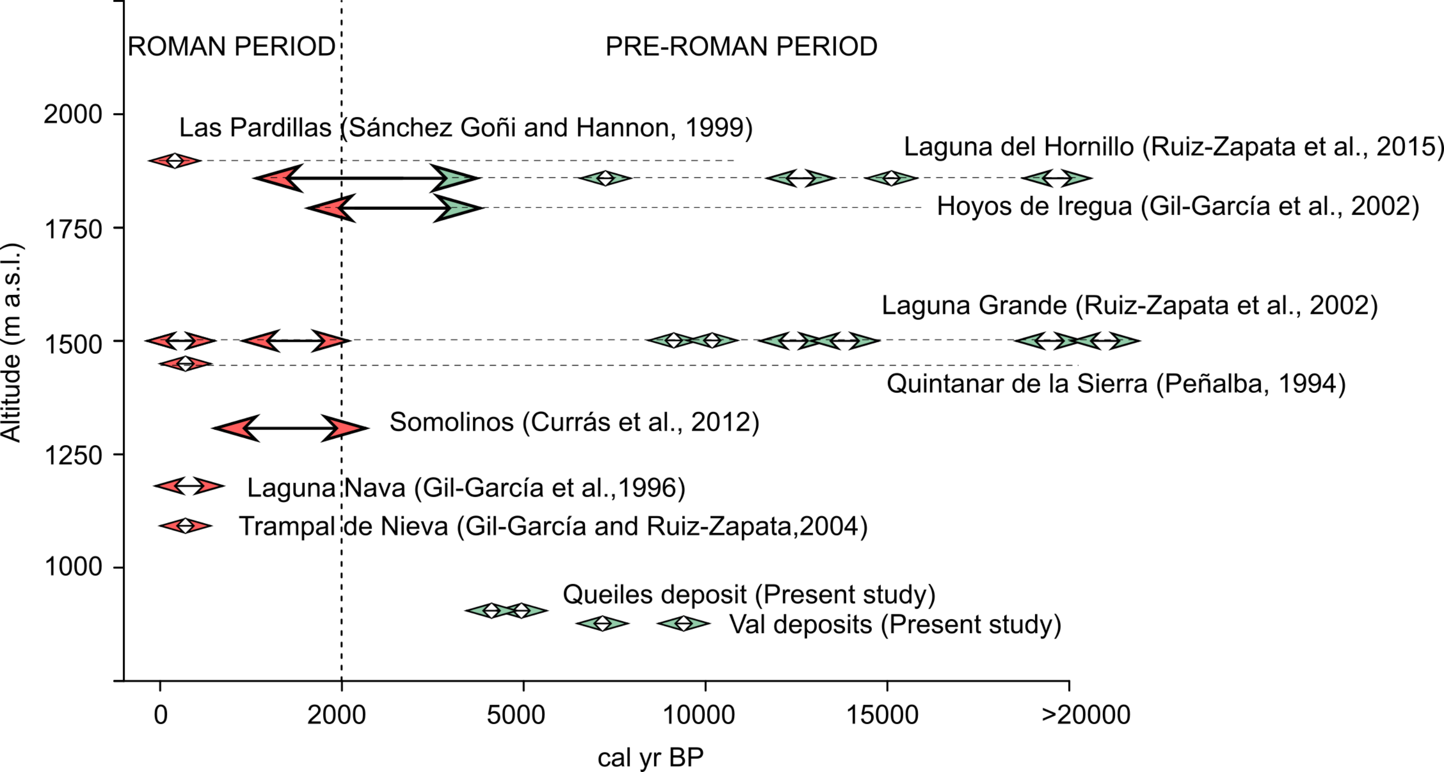
A
Queiles River tufa build-ups
South
North
A
B
C
D
E
F
G
Tread terrace
Thickness (m)
5825±27
4995±26
4135±24
4060±27
Queiles River
10 m
B
Val River tufa build-ups
West
East
1
2
3
10 m
Tread terrace
7180±33
7590±35
Val River
9540±35
Tread terrace
Pollen and charcoal samples
Phytoclast rudstones, plant and bryophyte bounstones
Massive and cross stratified oncoid rudstones
Gray marls with charcoal and gastropods
Gravels and sands
Slope blocks



QUEILES DEPOSIT
Pinus nigra/sylvestris type
Pinus pinaster/halepensis type
Taxus
Juniperus
Betula
Corylus
Salix
Populus
Ulmus
Fraxinus
Fagus
Juglans
Castanea
Quercus pyrenaica/faginea type
Mesophytes
Quercus ilex/coccifera type
Pistacia
Rhamnus
Phillyrea
Olea
Mediterranean taxa
Ericaceae
Calluna
Tamarix
Rosaceae
Viburnum
Hedera
Genista
Cytisus/Ulex type
Cistus
Helianthemum
Poaceae
Artemisia
Cichorioidae
Chenopodiaceae
Brassicaceae
Fabaceae
Lamiaceae
Herbs
Typha/Sparganium type
Typha latifolia type
Nymphaea
Hygro-hydrophytes
Pteridophyta
QUEILES-G
QUEILES-F
QUEILES-E
QUEILES-D
QUEILES-C
QUEILES-B
QUEILES-A
4060 cal yr BP
4135 cal yr BP
4995 cal yr BP
5825 cal yr BP
%
VAL-1 DEPOSIT
VAL-1 Top + 1m
VAL-1 Top
VAL-1 Base
7180 cal yr BP
7590 cal yr BP
VAL-2 DEPOSIT
VAL-2 Top
VAL-2 Base
9540 cal yr BP
VAL-3 DEPOSIT
VAL-3 Top
VAL-3 Base



2) Orihuela del Tremedal (1650 m a.s.l.)
10) Las Pardillas (1850 m a.s.l.)
8) Quintanar de la Sierra (1470 m a.s.l.)
cal yr BP
%
Albarracín Range
Northern Iberian Range
Moncayo Range
Ebro Basin
N
0 25 50 km
1) Villarquemado palaeolake (987 m a.s.l.)
11) Queiles tufa (854 m a.s.l.)
12) Val tufa (765 m a.s.l.)
QUEILES-G
QUEILES-F
QUEILES-E
QUEILES-D
QUEILES-C
QUEILES-B
QUEILES-A
4060 cal yr BP
4135 cal yr BP
4995 cal yr BP
5825 cal yr BP
VAL-1 Top + 1m
VAL-1 Top
VAL-1 Base
VAL-2 Top
VAL-2 Base
VAL-3Top
VAL-3 Base
7180 cal yr BP
7590 cal yr BP
9540 cal yr BP
Pinus
Betula
Corylus
Deciduous Quercus
Mesophytes
Pinus stomata
Evergreen Quercus
Mediterranean taxa


ROMAN PERIOD
PRE-ROMAN PERIOD
Las Pardillas (Sánchez Goñi and Hannon, 1999)
Laguna del Hornillo (Ruiz-Zapata et al., 2015)
Hoyos de Iregua (Gil-García et al., 2002)
Laguna Grande (Ruiz-Zapata et al., 2002)
Quintanar de la Sierra (Peñalba, 1994)
Somolinos (Currás et al., 2012)
Laguna Nava (Gil-García et al.,1996)
Trampal de Nieva (Gil-García and Ruiz-Zapata,2004)
Queiles deposit (Present study)
Val deposits (Present study)
Altitude (m a.s.l.)
2000
1750
1500
1250
1000
0
2000
5000
10000
15000
>20000
cal yr BP