The Holocene 19,8 (2009) pp. 1241–1255

Tracing the history of highland human management in the eastern Pre-Pyrenees: an interdisciplinary palaeoenvironmental study at the Pradell fen, Spain

Ana Ejarque,[1]* Ramón Julià,[2] Santiago Riera,[3] Josep Maria Palet,[1] Héctor A. Orengo,[1] Yannick Miras[4] and Carles Gascón[5]

([1]Catalan Institute of Classical Archaeology, Pl. Rovellat, s/n, 43003 Tarragona, Spain; [2]Institute of Earth Sciences Jaume Almera, Consejo Superior de Investigaciones Cientificas, C/ Lluis Sole Sabaris s/n, 08028 Barcelona, Spain; [3]Seminar of Prehistoric Study and Research, Department of Prehistory, Ancient History and Archaeology, University of Barcelona, C/Montalegre, 6, 08001 Barcelona, Spain; [4]GEOLAB (UMR 6042/CNRS), Maison des Sciences de l'Homme, Université B. Pascal, 4 rue Ledru, 6305, Clermont-Ferrand cedex 1, France; [5]Consell Comarcal de l'Alt Urgell, Passeig Joan Brudieu, 15, 25700 La Seu d'Urgell, Spain)

Received 6 April 2009; revised manuscript accepted 9 June 2009

A HOLOCENE RESEARCH PAPER

Abstract: Although high mountain areas have traditionally been viewed as predominantly grazing areas, with low population and a high degree of land-use stasis, recent research suggest that land-use complexity and change over time has been underestimated. This interdisciplinary palaeoenvironmental analysis has been carried out on the Pradell calcareous fen, located in the eastern Pre-Pyrenees (Spain) at 1975 m a.s.l., and it comprises different environmental indicators: pollen, stomata, non-pollen palynomorphs, macrocharcoal particles, lithostratigraphy, sedimentology and geochemistry. The results of this high temporal resolution study are integrated with archaeological data, and together provide strong evidence for the complexity of the high-mountain land-use system over the last 1500 years. Archaeological fieldwork has shown the rise of highland mining activities during the Roman period. Later, frequent fires resulted from the farming and settlement that followed the Christian conquest. Geochemical analysis of sediment cores records late-Mediaeval metal production, while the expansion of feudal cropping and the advent of several Mediaeval crises are clearly recorded in both the pollen and the historical data. Finally, the rise of a mixed economy system based on transhumance, farming, metallurgy and woodland exploitation was established during Modern and Contemporary times. The high correlation between the palaeoenvironmental, archaeological and historical data at the Pradell fen stresses the value of calcareous fens for palaeoenvironmental reconstructions of historical landscapes. Results obtained also depict high mountain landscapes as the result of the long-term interaction of many human practices, including mining and smelting, grazing, cropping and tree exploitation for the production of wood, charcoal and resin.

Key words: Pre-Pyrenees, calcareous fen, high mountain, multiproxy analysis, historical land use, palaeoenvironment, late Holocene.

Introduction

High mountain areas have traditionally been viewed as pristine environments with low population density and considered to be marginal areas for socioeconomic activities. The recent abandonment and depopulation of the highlands has strongly influenced this concept. However, archaeological and palaeoenvironmental research over the last two decades has produced growing evidence that European mountain regions are ancient human-managed landscapes with a notable human occupation that can be traced back to the Mesolithic period in some areas (Biagi and Nandris, 1994; Galop, 1998; Moe and Hjelle, 1999; Walsh and Richer, 2006; Miras *et al.*, 2007).

*Author for correspondence (e-mail: aejarque@icac.net)

10.1177/0959683609345084

This new concept of mountainous areas provides fresh insights into the understanding of present-day mountain environments by enhancing the role of human activities in the configuration of their landscape. Among these activities, grazing is regarded as the main practice carried out in high altitude areas and its importance in the Pyrenees has indeed been proved from the Neolithic until recent historical times, (Galop, 1998; Rendu, 2003; Ros, 2004; Codina, 2005; Miras *et al.*, 2007; Palet *et al.*, 2007; Mazier *et al.*, 2009). However, the straightforward characterisation of highlands as mainly grazed areas during the past should be questioned. In this respect, the archaeological wealth documented in mountain areas actually accounts for the existence of a high complexity and variety of human practices, including grazing, cropping, mining and smelting, woodland exploitation (charcoal, resin and rosin production, tree felling) and commercial activities (Rendu, 2003; Walsh and Richer, 2006; Jouffroy-Bapicot *et al.*, 2006; Palet *et al.*, 2007; Ejarque and Orengo, 2009). An integrated multiproxy palaeoenvironmental, archaeological and historical approach is deemed necessary to properly define the history of complex socioeconomic systems, as underlined by the IGBP-PAGES Focus 5 programe on 'Past ecosystem processes and human–environment interactions' (Dearing *et al.,* 2006).

Most palaeoenvironmental studies have focused on the axial Pyrenean ranges (Figure 1) using lake sediments (Jalut, 1974; Montserrat, 1992; Reille and Lowe, 1993; Camarero *et al*., 1998; Guiter *et al*., 2005; Pla and Catalan, 2005; González-Sampériz *et al*., 2006, etc.) and peat bog sequences (Jalut *et al*., 1992; Gómez and Esteban, 1993; Galop, 1998; Miras *et al*., 2007; Mazier *et al*., 2009). Dendroclimatological series for historical periods are also available in these axial ranges (Creus and Saz, 1999; Büntgen *et al*., 2008). However, very few studies have been carried out in the Pre-Pyrenean ranges (Montserrat, 1992; Riera *et al*., 2004) where carbonate rocks predominate and few lakes and peatlands are available. Among these wetlands, alkaline peatlands are the most frequently recorded, although they have been poorly checked in palaeoecological studies applying multiproxy analyses (Boyer and Wheeler, 1989; Almendinger and Leete, 1998).

This paper aims to trace human management and landscape shaping of high altitudinal spaces during the last 1500 years. To achieve this, archaeological and historical data have been cross-checked with environmental indicators, namely, pollen, stomata, non-pollen palynomorphs (NPPs), macrocharcoal particles, lithostratigraphy, sedimentology and geochemistry. This study follows the perspective suggested by Dearing *et al*. (2006) underlining the need to study well-documented case studies on a local level as the most suitable approach to analysing human–environment interactions.

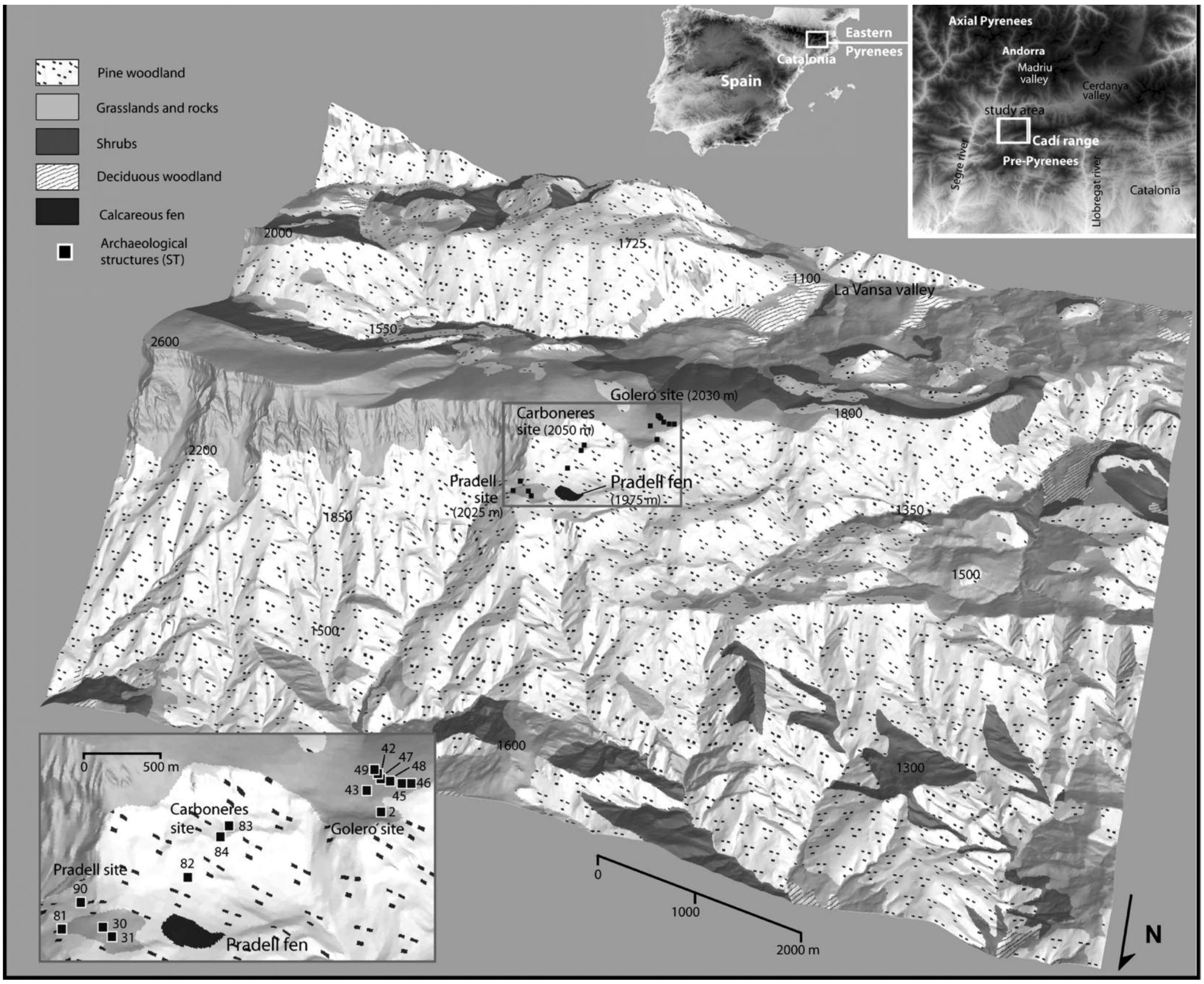

Figure 1 Vegetation map showing the Cadí range and the location of the Pradell fen and the archaeological structures in the study area. See Table 1 for detailed description of the archaeological structures

Table 1 AMS radiocarbon results from archaeological sites located in the vicinity of the Pradell fen

Laboratory reference	Archaeological structure	Archaeological site	Conventional age (^{14}C yr BP)	Calibrated age (2σ) (cal. yr AD)	Type of structure
Poz-18805	ST 82	Carboneres	630 ± 30	1287 (1342) 1398	Charcoal mound
Poz-18802	ST 84	Carboneres	360 ± 25	1452 (1542) 1633	Charcoal mound
Poz-18806	ST 83	Carboneres	225 ± 30	1641 (1723) 1805	Charcoal mound
Poz-18801	ST 31	Pradell	1740 ± 30	235 (311) 388	Livestock enclosure
Poz-18779	ST 81	Pradell	1330 ± 30	648 (709) 770	Mine tailing
Poz-24490	ST 90	Pradell	690 ± 30	1266 (1326) 1387	Charcoal mound
Poz-18785	ST 30	Pradell	30 ± 30	1696 (1825) 1955	Pastoral hut
Poz-18786	ST 43	Goleró	2125 ± 30	210 (130) 51	Kiln
Poz-13615	ST 02	Goleró	1695 ± 30	256 (366) 416	Livestock enclosure
Poz-225674	ST 47	Goleró	310 ± 30	1487 (1568) 1649	Livestock enclosure
Poz-18803	ST 48 SU 103	Goleró	165 ± 30	1662 (1807) 1953	Livestock enclosure
Poz-18788	ST 48 SU 104	Goleró	160 ± 30	1664 (1808) 1953	Livestock enclosure
Poz-22571	ST 46	Goleró	155 ± 30	1666 (1809) 1953	Livestock enclosure
Poz-28433	ST 45	Goleró	150 ± 30	1667 (1810) 1953	Livestock enclosure

Dates have been calibrated using CALIB 5.0 (Reimer *et al.*, 2004). The dates in parentheses correspond to the mid-point of the calibration range.

Site description and archaeological context

The Cadí range is an east–west trending major structure in the eastern Pre-Pyrenees of Spain (Figure 1). These Pre-Pyrenean ranges are formed by folded structures of sedimentary rocks (Vergés *et al*., 1992). The Cadí range is characterised by an abrupt verticality ranging from 700 to 2648 m a.s.l. and by deep, narrow valleys and steep summits of rough relief. This *c*. 24 km long mountainous range is bordered by the Segre and Llobregat rivers. The climate of the Cadí range is influenced by this verticality and can be described as axeromeric sub-Mediterranean at low and mid altitudes and subalpine and alpine cold-axeric at the highest altitudes (Carreras *et al*., 1995). A mean annual rainfall of 1025 mm and a mean annual temperature of 7.1°C, with temperate summers (13.8°C) and winters (1.7°C), are recorded at 1830 m a.s.l. (Port del Compte Meteorological Station) (Vigo *et al*., 2003). The Cadí range was designated the Cadí-Moixeró Natural Park in 1983.

The vegetation of the study area is characterised by calcicolous pine woodland (*Pulsatillo-Pinetum uncinatae*), which reaches 2000–2200 m a.s.l. (Figure 1). Calcicolous alpine grasslands from the *Festucion scopariae* plant community are found mainly on the southern slope between 1900 and 2300 m a.s.l. (Figure 1). Below 1800 m a.s.l. montane calcicolous Scots pine woodland (*Pinus sylvestris*) develops. Below 1500–1000 m a.s.l. the submontane belt is mainly composed of mixed Scots pine and oak woodland of the *Buxo sempervirentis-Quercetum pubescentis* plant community (Vigo *et al.*, 2003). On the southern slope, shrub communities of *Buxus sempervirens* and, to a lesser extent, *Quercus rotundifolia*, extend down to 1350 m a.s.l. (Vigo *et al.*, 2003).

The Pradell fen (42°17′20″N; 1°32′52″E) is located at 1975 m a.s.l. on the westernmost part of the northern slope of the Cadí range, within the subalpine belt (Figure 1). The fen forms a small inclined basin (1.92 ha) on the northern slope and is fed by underground water. Pradell is an alkaline peatland covered by the *Caricetum davallianae* plant community, characterised by the prevalence of *Carex davalliana* and *C. paniculata* (Vigo *et al*., 2006).

Archaeological fieldwork has been carried out in the subalpine and alpine belt of the Cadí range from 2004. Extensive surveying has resulted in the recording of 107 archaeological structures, including pastoral sites, circular Pyrenean enclosures, charcoal mounds, metallurgical furnaces and cropping terraces (Palet *et al*., 2007). Archaeological excavations were mainly carried out on the western side of the range, where the Pradell fen is located. In this paper, structures from the Pradell, Carboneres and Goleró sites, located in the vicinity of the Pradell fen (Figure 1) and spanning the last 2000 years, have been included in the discussion. Structures were radiocarbon dated at the Poznań Radiocarbon Laboratory using stratigraphically contextualised macrocharcoal remains (Table 1). Dates were calibrated using the CALIB 5.0 program (Reimer *et al.*, 2004). In addition to the radiocarbon dating, the finds of diagnostic Roman pottery in three excavated iron furnaces (ES 42, ES 43 and ES 49) is proof of the continued use of these structures up to the second century AD (Palet *et al*., 2009). Equally, the recovery of Modern-period pottery in the final occupation levels of some livestock enclosures (ES 02 and ES 31) at the Pradell and Goleró sites evidence their use between the seventeenth and the nineteenth centuries AD.

Materials and methods

In September 2005, coring was carried out in the Pradell fen using a 50 cm × 5 cm 'Russian' corer. A 180 cm long core was extracted from the southeastern edge of the peatbog close to the pine woodland. Sections of the core were taken at 1 cm intervals and a high resolution multiproxy study of the samples, consisting of pollen, non-pollen palynomorphs (NPP), macrocharcoal particles, sedimentology and geochemistry analyses, was carried out.

Sedimentology/geochemistry

Water content was calculated using an oven at 60°C. These samples were also used to calculate the weight percent organic matter and carbonate content by weight loss achived after 4 h of burning sediment at 550°C and at 950°C in a muffle furnace (Dean, 1974; Heiri *et al*., 2001). The geochemical analysis for K, Na, Mg, Ca, Sr, Ti, Al, Fe, Mn, Cr, Co, Ni, Cu, Zn, As and Pb was performed every 2–4 cm using ICP-AES (Inductive Coupled Plasma) at the Institute of Earth Science-CSIC (Barcelona). Treatment of samples for geochemical analysis was carried out at the U-series dating Laboratory of the Institute of Earth Science. The dried sample was milled in an agate mortar for x-ray diffraction in order to determine the mineralogical composition (calcite, gypsum, quartz, hematites and clays). Subsequently, these samples were used for total acid dissolution in 25 ml PTFE beakers following the procedures described in Luo and Ku (1991). Geochemical values were normalised using the Ti content (Covelli and Fontolan, 1997). Zones were established using CONISS (Grimm, 1987) with some minor modifications based on lithological changes.

Table 2 AMS radiocarbon results from the Pradell fen

Laboratory reference	Depth (cm)	Material	Conventional age (^{14}C yr BP)	Calibrated age (2 σ) (cal. yr BC/AD)	Age used for the chronological model
Poz-19400	82	Wood	360 ± 30	AD 145–1634	AD 1542 ± 92
Poz-19401	135	Peat	965 ± 30	AD 1019–1155	AD 1087 ± 68
Poz-13713	161	Charcoal	1240 ± 30	AD 686–873	AD 780 ± 94

Dates have been calibrated using CALIB 5.0 (Reimer *et al*., 2004).

Pollen, NPPs and macrocharcoal particles

Samples were analysed using standard pollen preparation procedures (Faegri *et al*., 1989) which included treatment with KOH, sieving at 200 μm, hot HF, HCl, acetolysis and mounting in glycerine jelly. *Lycopodium clavatum* spore tablets were added in order to calculate pollen and NPP concentrations (Stockmarr, 1971). Pollen, stomata, NPP and macrocharcoal concentration values are expressed in grams of dry sediment. Pollen, NPPs and stomata were identified and counted on a Zeiss Axioscop 40 microscope at 500× magnification. Macrocharcoal particles >200 μm were counted using a Zeiss Stemi 2000-C binocular microscope at 80× magnification. Pollen, NPP and stomata identification followed published illustrations and morphological keys (Faegri *et al*., 1989; Moore *et al*., 1991; Reille, 1992; Hansen, 1995; van Geel, 2001; van Geel and Aptroot, 2006). Pollen percentages were calculated as a percentage of Total Land Pollen (TLP), excluding aquatic plants and ferns, and the local taxa Cyperaceae and Cichoroideae.

The ruderal and nitrophilous summary curve include pollen taxa indicative of human impact (Behre, 1981), including those underlined by pollen studies performed in high mountain environments (Galop, 1998; Brugiapaglia *et al*., 1998; Court-Picon *et al*., 2005; Mazier *et al*., 2009). In total, 38 samples were counted along the core every 5 cm, which represents intervals between samples of *c*. 25 years in the upper part of the core and *c*. 50 years in the lower part. Minimum pollen counts of 600 dry land pollen grains and at least 200 NPPs and 100 fungal spores were made. NPPs and macrocharcoal are reported in diagrams as concentration values. Diagrams were plotted using the C2 program (Juggins, 1991) and pollen and NPP biozones were established using CONISS (Grimm, 1987) with some minor modifications (Birks and Birks, 1980).

Radiocarbon data

Three ^{14}C AMS dating measurements were obtained at the Poznań Radiocarbon Laboratory using wood, charcoal and peat material. Dates were calibrated using the CALIB 5.0 program (Reimer *et al*., 2004). The chronology for the last 100 years was inferred from the sediment Pb concentratrion. Geochemical analyses (see Geochemistry section) record a Pb increase in the uppermost 15 cm of the sequence, with a peak at a depth of 5–7 cm. This increase has been widely observed in European lakes (Kober *et al*., 1999; Lotter *et al*., 2002) and has been attributed to the industrialisation process recorded in the Pyrenees at *c*. 1875/1900 (Rose, 1999) and a subsequent lead maximum contamination during the 1960s. These dating events have been included in the chronological model.

Results

Chronological model

Radiocarbon dates for the Pradell fen are presented in Table 2. An age–depth model has been established plotting calibrated radiocarbon dates versus depth and assuming constant sedimentation rates between adjacent pairs of dates (Figure 2). Pradell data support continuous sediment accumulation over the last 1500 years. The adopted chronological data appear consistent with historical data.

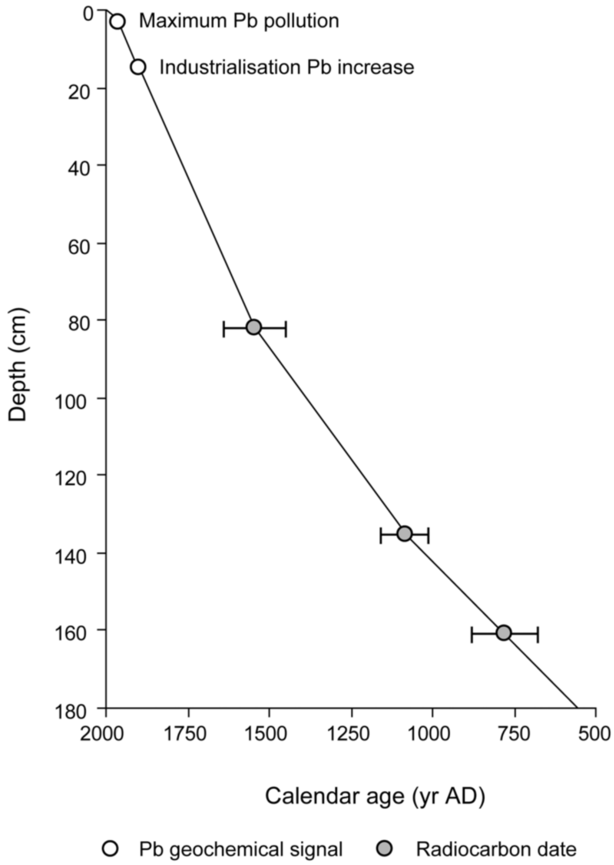

Figure 2 Age–depth model of the Pradell sequence constructed with calibrated radiocarbon dates and Pb measurements

Lithology (Figure 3)

The 180 cm long Pradell sequence records three major organic layers interbedded with brownish silty clays. Eight lithozones were differentiated on the basis of mineralogy, lithology and sedimentary structures:

Lithozone 8 (180–168 cm depth) consists of red clay with gravels.
Lithozone 7 (168–147 cm depth) consists of silty clays dark brown in colour with occasional charcoal particles.
Lithozone 6 (147–133 cm depth) is formed by a peat bed, black in colour, with wood fragments. Thin laminae of reddish silty clays with charcoal remains occur from 145 to 147 cm depth. This organic bed contains gypsum and haematites.
Lithozone 5 (133–74 cm depth) consists of massive silty clay, dark brown to greyish in colour. Occasional thin reddish laminae and charcoal particles are present. A lamina of silty clay rich in organic matter occurs between 80 and 82 cm.
Lithozone 4 (74–66 cm depth) consists of light brown peat interbedded with brownish clays.
Lithozone 3 (66–17 cm depth) corresponds to massive reddish brown silty clays with abundant vegetal fibres and charcoal fragments. The bottom 9 cm has a dark brown colour.

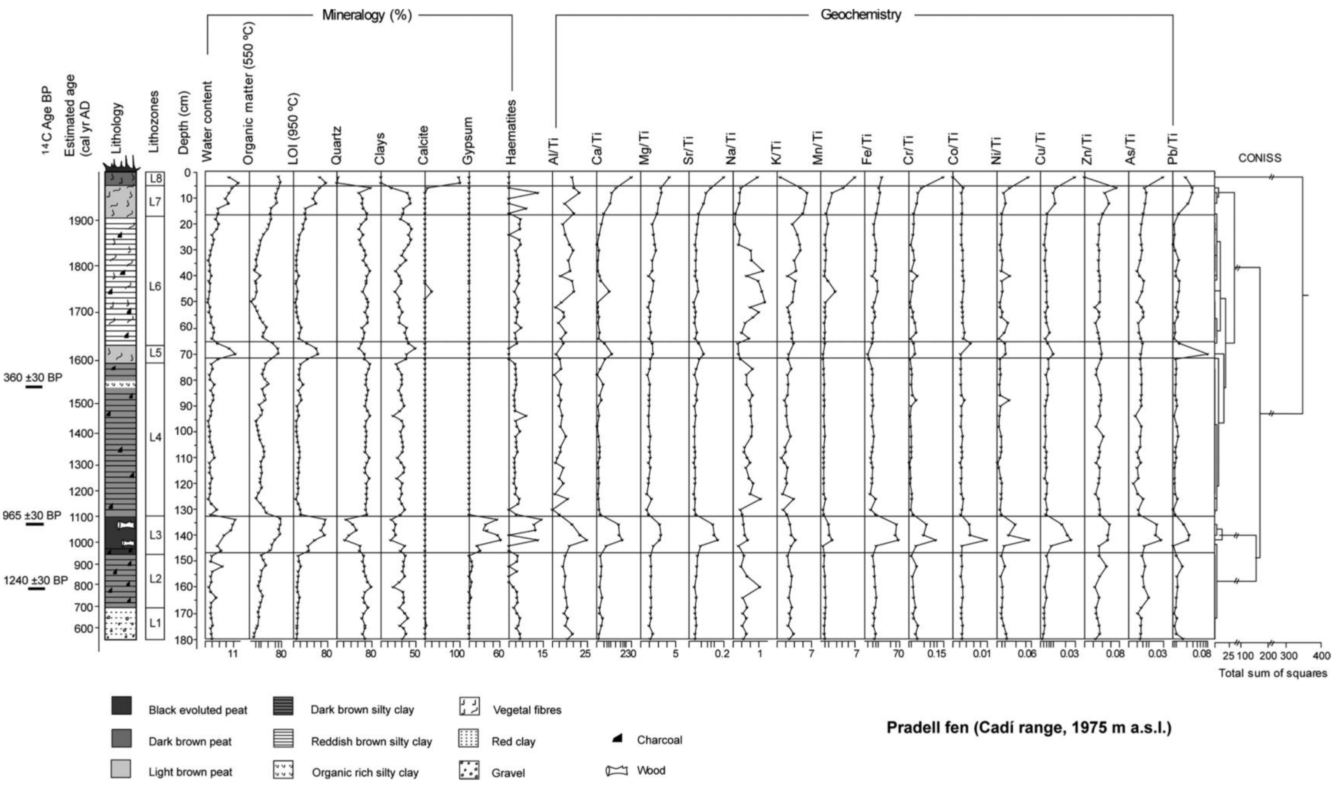

Figure 3 The lithology, water content, organic matter content, mineralogy and geochemical results of the Pradell record

Lithozone 2 (17–5 cm depth) is characterised by light brown peat with thick fibres.

Lithozone 1 (5–0 cm depth) consists of dark brown peat.

Organic matter content

Figure 3 shows the high correlation between water content, organic matter and LOI, allowing us to distinguish three layers of high organic matter content that correspond to geomorphologically stable phases which allow peat development. The uppermost peat layer (lithozones 8 and 7) shows a progressive organic matter increase from 10% at a depth of 27 cm to 70% at 5 cm depth, corresponding to the most recent peat development. The second peat layer (lithozone 5) is thinner and records lower organic content (50%). It coincides with an increase in metal content. The third peat layer (lithozone 3) reaches a high organic matter content (70%) and records the presence of gypsum as well as high values of metals such as Fe, Cu, Ni, Cr and As.

Geochemistry

The geochemical data show clear relationships between variation in sedimentology, water, organic and carbonate content over time (Figure 3). Seven zones can be defined which correlate clearly with important changes in organic matter content.

From 180 to 147 cm all metals are present in low concentrations, while minor oscillations are recorded in siliciclastic sediments. Between 147 and 133 cm all metals show a noticeable increase related to low siliciclastic input and major organic matter content. In this level, gypsum and haematites are also recorded. Between 133 and 72 cm all metals maintain background values, with minor variations coeval with a major siliciclastic contribution. In addition, minor peaks of Cr, Co and Ni are recorded at a depth of 88 cm. From 72 to 65 cm a second phase of inferred metal pollution is recorded, although much less marked than the earlier phase. Between 65 and 17 cm metal composition follows background levels with minor oscillations, although variations in Cr, Ni, As and Pb content are recorded. From 17 to 5 cm all metals record an increase probably related to recent anthropogenic activities. During this phase, which corresponds to the upper peat layer, haematites also increase. There is a marked decrease in concentration of some metals in the top 5 cm of the sequence, including Pb, Zn and Co, which coincides with a noticeable increase in calcite, Cr, Ni, Cu and As.

Pollen zones, stomata and macrocharcoal results (Figure 4)

PRA-1 (180–147 cm)

This zone records high percentages of Arboreal Pollen (AP), mainly composed of *Pinus* (58–74%). However, *Pinus* pollen concentrations are low, from *c.* 20 000 to 70 000 grains/g. High percentages of herbs are otherwise present, showing average values of 35%. Poaceae (14%), Cichoroideae and Apiaceae are the most abundant herbs, but ruderal and nitrophilous taxa such as *Plantago, Plantago lanceolata*-type, *Rumex*, *Cirsium*-type, Asteroideae, *Polygonum aviculare*-type and *Urtica dioica*-type are also recorded. Cichoroideae reaches the maximum percentages in the sequence. *Abies* and temperate trees such as *Betula*, *Alnus glutinosa*, *Corylus*, deciduous *Quercus* and *Quercus ilex*-type are recorded with low percentages. Point notations of the Cerealia-type are present. Macrocharcoal concentration is high and increases to as much as 123 particles/g in the upper part of the zone.

PRA-2 (147–137 cm)

In this zone *Pinus* reaches a maximum of 90%, whereas Poaceae decrease sharply to 1.5%. The occurrence of *Pinus* close to the drilled site is corroborated by the increase in *Pinus* stomata, which register the highest concentration values of the profile. The regression of herbs is general in the zone with the exception of Liliaceae, which increase to 7%. Mediterranean and temperate trees and shrubs such as *Quercus ilex*-type and *Corylus* show a regression pattern, while the first presence of *Juglans* is registered. Macrocharcoal concentration decreases to 9 particles/g and remains low in the zone.

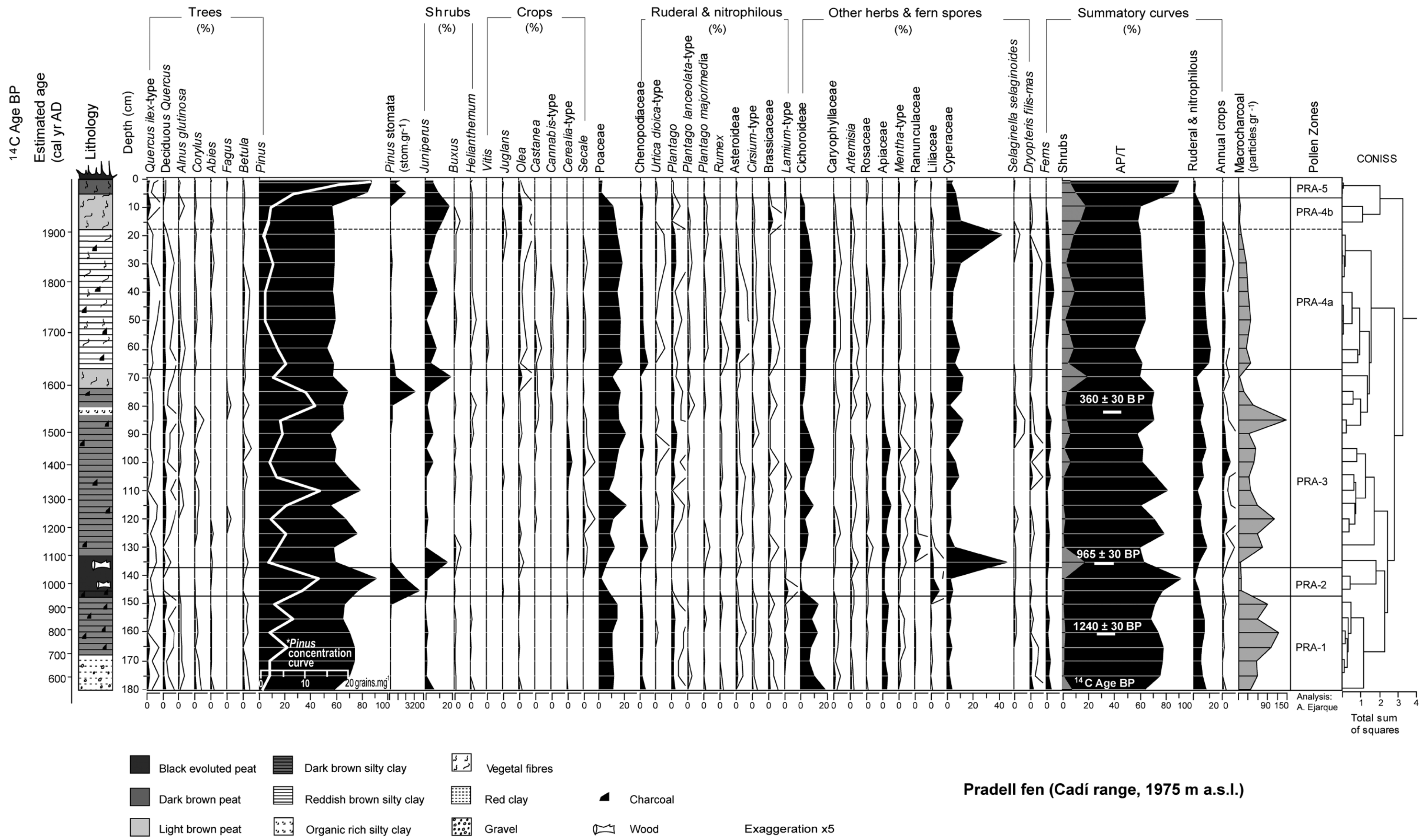

Figure 4 Main pollen taxa, *Pinus* stomata and macrocharcoal diagram of the Pradell sequence. Pollen values are expressed in percentages, while stomata and macrocharcoal are expressed in concentration per gram of dry sediment. The white line within the *Pinus* percentage curve represents *Pinus* concentration values per milligram of dry sediment

PRA-3 137–68 cm)

Arboreal pollen exhibits an oscillating pattern throughout this zone, with three regression phases followed by woodland regeneration, reaching 80%. This variability is mainly representative of *Pinus* pollen behaviour, whose percentage oscillations can be also observed through concentration values. Although *Pinus* stomata disappear during the zone, a second peak is evidenced at the uppermost part simultaneously with the last *Pinus* regeneration episode. Temperate taxa such as deciduous *Quercus* also show this oscillating pattern, whereas *Corylus* and *Betula* reappear. *Abies* disappears during this zone and *Fagus* is recorded for the first time. Among the shrubs, *Juniperus* shows an isolated peak during the first episode of AP reduction at the beginning of the zone, which is followed by its increase towards the uppermost part. Herbs, especially Poaceae, reach the highest percentages of the profile, with values of 46% and 21%, respectively. Ruderal and nitrophilous taxa, especially *Plantago*, Asteroideae and Chenopodiaceae, show a general increasing trend. A peak of Cyperaceae appears at the beginning of the zone. An increase in Cerealia-type (4%) and *Secale* is observed, while other crops such as *Cannabis*-type and *Castanea* are recorded for the first time. Macrocharcoal concentration increases, reaching the maximum values of the profile in the upper part of the zone (147 particles/g).

PRA-4 (68–7 cm)

A continuous retreat of *Pinus* values is noticeable along the zone, reaching minimum pollen percentages of 52%, as well as low concentration values of 10 420 grains/g. *Pinus* percentages remain stable while *Pinus* stomata disappear. Among other arboreal taxa, *Abies* reappears and the *Quercus ilex*-type records a slight increase. The shrub community is now better represented, with an increase of *Juniperus*. The opening of the landscape is indicated by an increase in herbs, which reach 40%. Macrocharcoal concentration is low along the zone, with values of 37 particles/g.

Two subzones can be distinguished regarding the increase of *Juniperus* and *Olea* in the upper subzone (PRA-4b). Also during PRA-4b, ruderal and nitrophilous taxa are reduced, *Urtica dioica*-type and *Plantago lanceolata*-type, Cerealia-type, *Secale*, *Cannabis*-type and *Castanea* disappear. A peak of Cyperaceae is also noticeable in the upper part of the subzone PRA-4a.

PRA 5 (7–0 cm)

The zone records a strong increase in AP reaching 90%, which is mainly composed of *Pinus* (87%). The concentration of *Pinus* is the highest in the profile (25 320 grains/g), while *Pinus* stomata reappear. Herb taxa, mainly Poaceae, fall to record their minimum values. Ruderal and nitrophilous taxa decrease and crop taxa disappear, while macrocharcoal concentrations show insignificant values of less than 1 particle/g.

NPP zones (Figure 5)

Twenty-seven NPP types have been identified in the Pradell fen. These types correspond to fungal spores (19 types), algae (three types), faunal remains (four types) and protozoa (one type). See Figure 5.

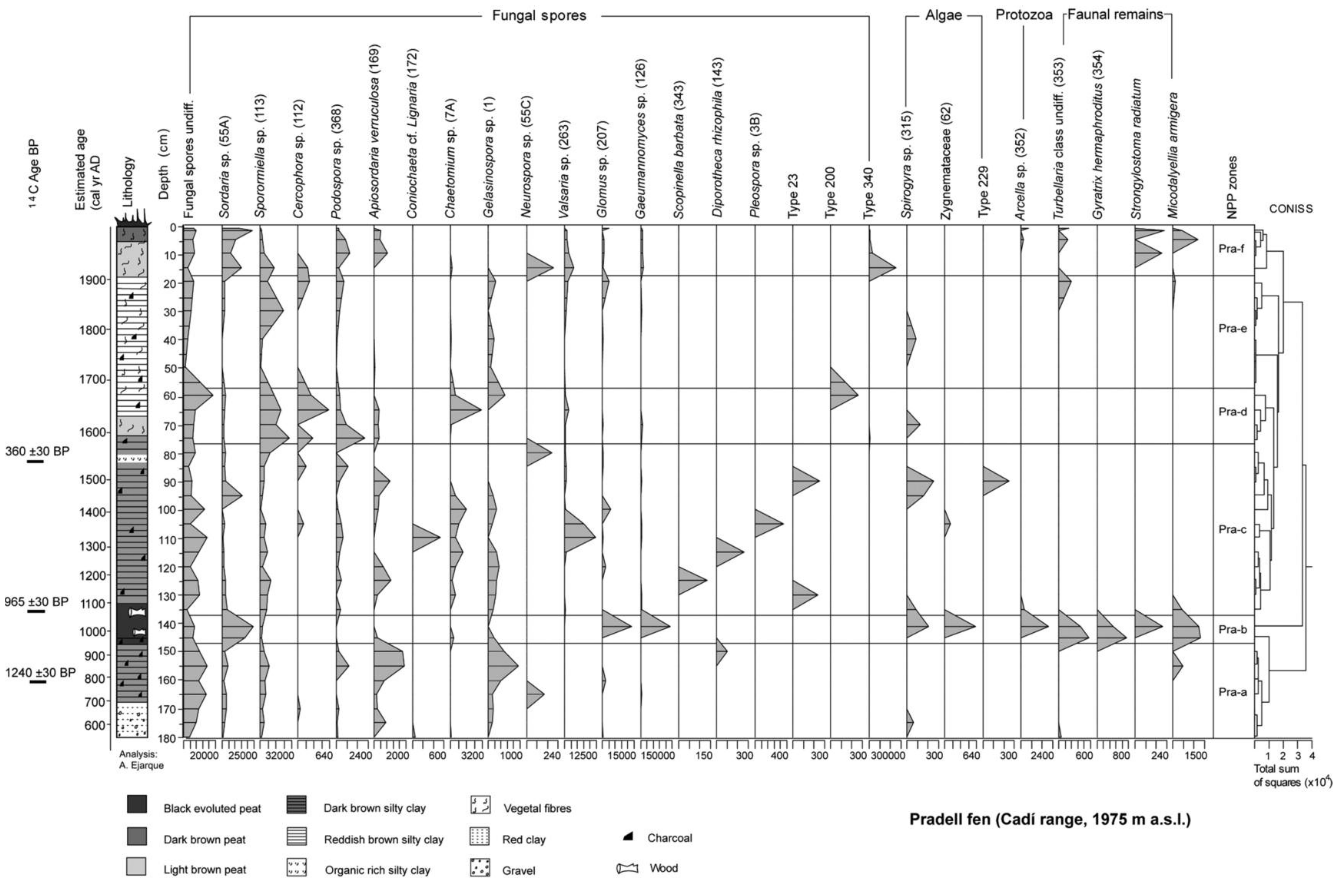

Figure 5 Selected NPP diagram of the Pradell sequence. NPP values are expressed in concentration per gram of dry sediment

Pra-a (180–147 cm)

Fungal spores dominate the NPP assemblage. Undifferentiated fungal spores and *Apiosordaria verruculosa* (169) present high values of *c*. 15 000 spores/g and *c*. 1880 spores/g, respectively. An increase of *Gelasinospora* sp. is recorded in the upper part of the zone. Continuous curves of *Sordaria* sp. and *Sporormiella* sp. are registered, while other fungal spores such as *Podospora* sp., *Cercophora* sp., *Coniochaeta* cf.. *lignaria* (172), *Diporotheca rhizophila* (143) and *Neurospora* sp. are recorded at certain points.

Pra-b (147–137 cm)

Undifferentiated fungal spores and *Apiosordaria verruculosa* (169) are replaced by a significant increase in *Sordaria* sp. reaching *c*. 2440 spores/g. *Gelasinospora* sp. and *Sporormiella* sp. retreat, while peaks of *Glomus* sp. and *Gaeumannomyces* sp. are recorded. An increase of the NPP richness is recorded during the zone, with the concurrence of simultaneous peaks of *Spirogyra* sp., Zygnemataceae, oocyst of the Turbellaria class and the protozoa *Arcella* sp.

Pra-c (137–77 cm)

A more diversified fungal spore assemblage and decreases in algal, protozoa and faunal remains are registered during this zone. *Sordaria* sp. falls and there is an increase in undifferentiated fungal spores, *Chaetomium* sp., *Gelasinospora* sp. and, to a lesser extent, *Sporormiella* sp. A significant increase in *Valsaria* sp. (263) to *c*. 12 300 spores/g and Type 495 to *c*. 8000 spores/g is recorded in the middle of the zone, while *Scopinella barbata* (343), *Pleospora* sp. (3B) and Type 23 are recorded for the first time.

Pra-d (77–57 cm)

NPP richness decreases in this zone. Among the fungal spores, the increase of *Sporormiella* sp. (*c*. 2950 spores/g), *Cercophora* sp. (*c*. 620 spores/g) and *Podospora* sp. (2120 spores/g) is noteworthy. A peak of *Chaetomium* sp. is registered in the middle of the zone, while the increase of *Gelasinospora* sp. and a peak of Type 200 are also observed in the upper part of the zone.

Pra-e (57–18 cm)

NPP richness remains low during the zone, while the retreat of undifferentiated fungal spores is observed. Although *Sporormiella* sp., *Cercophora* sp. and *Podospora* sp. fall significantly at the beginning of the zone, they recover in its uppermost part.

Pra-f (18–0 cm)

A more diversified and abundant NPP assemblage is noticeable. Among the fungal spores, *Sordaria* sp. and Type 340 increase, while *Sporormiella* sp., *Cercophora* sp. and *Podospora* sp. retreat progressively. Peaks of Neorhabdocoela oocytes are recorded, together with the presence of *Arcella* sp. (352).

Discussion (Figure 6)

Based on the integration of multiproxy data with the archaeological and historical data, six palaeoenvironmental phases can be recognised during the last 1500 years. These phases reflect the main environmental changes and land uses in the local dynamic of this high mountain area.

Phase I (AD 525 ± 100 to 950 ± 80: 180–147 cm). The first stable settlements after an unstable transition period

During this phase the sediment corresponds to a slope deposit characterised by red clays with gravels overlaid by massive dark brown silty clays containing charcoal particles. The identification of mottled and bioturbation features suggest an incipient pedogenic process affecting the colluvial deposit. However, the diversity of the pollen and NPP taxa attest for the stratigraphic integrity of the sediment.

The low pollen concentration levels of *Pinus* and high percentages of herbaceous pollen suggest the prevalence of a relatively open pine woodland in the subalpine belt. *Pinus* percentages are relatively high during the zone, although they do not reach 80%, the estimate value for dense pine woodland, as indicated by modern pollen assemblages in high mountain areas. Recorded pine percentages can therefore be the result of *Pinus* pollen over-representation in mountain contexts (Brugiapaglia *et al*., 1998; Court Picon *et al*., 2005).

Montane woodland was formed by silver fir and temperate trees such as *Betula*, *Alnus glutinosa*, *Corylus*, deciduous *Quercus* and *Quercus ilex*-type. Although the presence of ruderal and nitrophilous herbs, such as *Plantago* sp., *Plantago lanceolata*-type, *Rumex*, *Cirsium*-type, Asteroideae, *Polygonum aviculare*-type and *Urtica dioica*-type support the existence of grazing activities at this time, the moderate abundance of local coprophilous fungi, such as *Sporormiella* sp., *Cercophora* sp. or *Podospora* sp., suggests a low impact of such activities near Pradell (Blackford and Innes, 2006; Davis and Shafer, 2006; van Geel and Aptroot, 2006). This low local impact is otherwise supported by the fact that most ruderal and nitrophilous pollen taxa recorded during this zone are likely to represent more regional human activities in the fossil pollen record, as indicated by studies of mountain modern pollen assemblages (Court Picon *et al*., 2005; Mazier *et al*., 2009).

On the other hand, isolated recording of Cerealia-type suggest moderate cropping activities at lower altitudes. The significant macrocharcoal abundance and the synchronous recording of fire-related fungi (*Gelasinospora* sp. and *Neurospora* sp.) indicate that local fires took place close to the site (Carcaillet *et al*., 2001; Blackford *et al.,* 2006), while macrocharcoal identification corroborates the evidence that fire affected the subalpine pine woodland.

Archaeological excavation of three furnaces at the Goleró site (ST 42, ST 43 and ST 49) has proved the existence of iron mining and smelting activities in the zone during Roman times, between the first century BC and second century AD. Moreover, human presence is also documented at the Pradell and Goleró archaeological sites (ST 31 and ST 02) during late Roman times (third to fifth centuries AD) (Palet *et al*., 2009) (Figure 1). During this phase, metal content at the Pradell fen, which does not reach background levels, suggests a moderate mining and smelting activity. These mining activities are also supported by the recording of mine tailings at the Pradell site (ST 81), which has been dated to AD 709. These former activities may explain the relatively open woodland recorded at Pradell.

Written accounts indicate that during the eighth century this was a frontier area between the Muslims and the Christians. This politically unstable period is therefore consistent with the high frequency of fires and the moderate grazing and cropping activities recorded throughout this phase. This territory would not be brought back into the Christian domain until 849, when written sources record the existence of a church, vineyards and a mill in the La Vansa valley (Baraut, 1986) (Figure 1). From the mid-ninth century onwards, a human-managed landscape comes about through a process of stable settlement, which included the farming of new fields created by clearing woodland. This land management process, referred to in the Christian written sources as 'rompudes' (Bonnassie, 1979; Salrach, 2004), could explain the increase in the frequency of fires documented at Pradell between AD 750 and 900. In this respect, the La Vansa valley toponym 'Rot', which is derived from the Latin word *ruptus*, corroborates the occurrence of these farming clearances (Gascón, 2009). Similar processes of fires and farming expansion are also reported at this time in other Pyrenean and Pre-Pyrenean areas (Jalut, 1974; Galop, 1999; Riera *et al*., 2004).

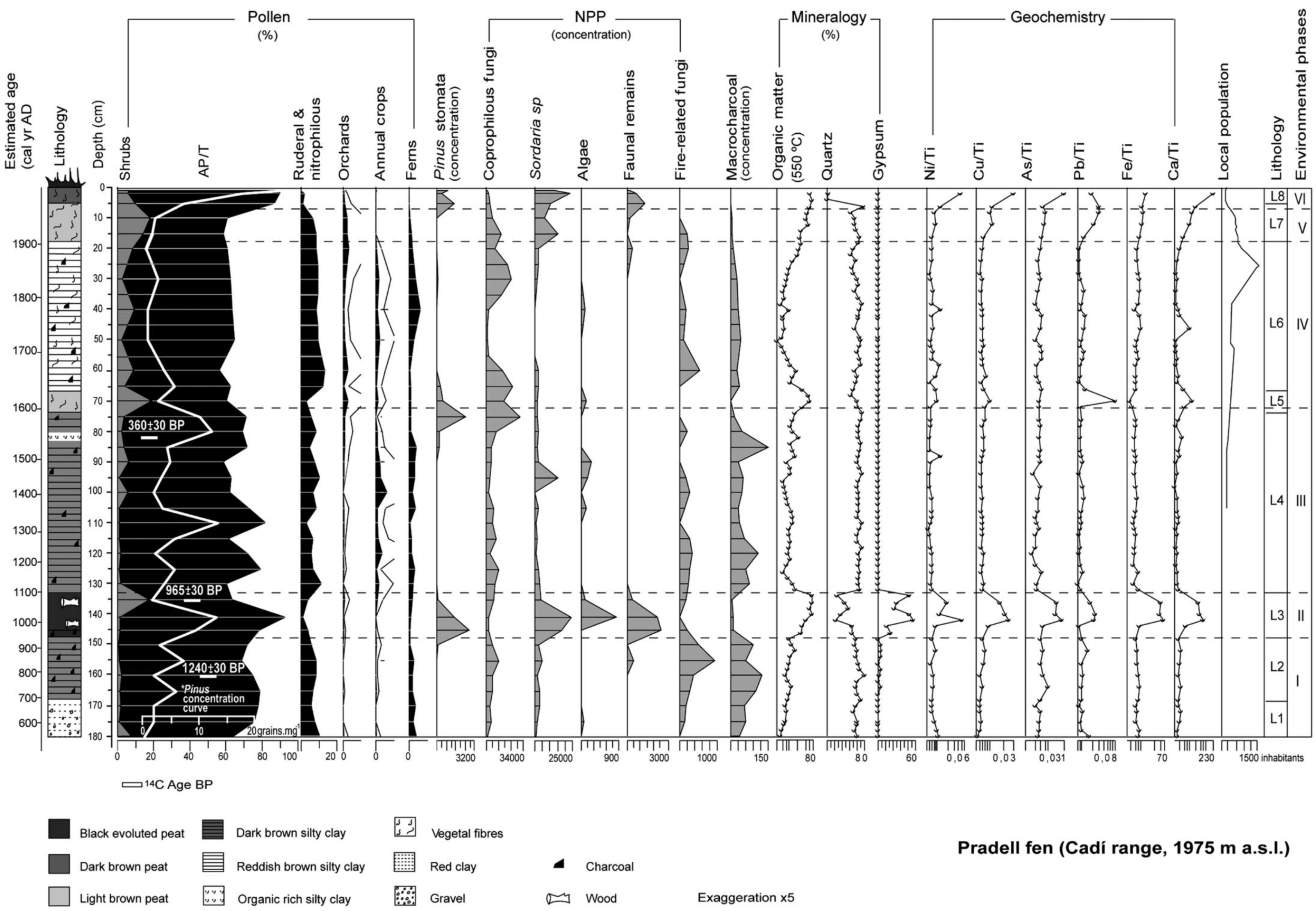

Figure 6 Summary of key proxies and environmental phases established in the Pradell fen. Radiocarbon dates of archaeological structures and the local population curve are included in the figure. The white line within the *Pinus* percentage curve represents *Pinus* concentration values per milligram of dry sediment

Phase II (AD 950 ± 80 to 1100 ± 80: 147–133 cm). The rise of Mediaeval metal production

This phase corresponds to the lower peat layer of the profile. From a geomorphological point of view, the occurrence of a peat layer implies a change towards a reduction in the slope dynamics and more stable water-table. The expansion of Cyperaceae indicates the development of a sedge fen in the uppermost part of this peat level. Local predominance of Cyperaceae is otherwise underlined by peaks of *Gaeumannomyces* sp. (126), previously correlated with sedge-phases in raised bogs (van Geel, 1986). Moreover, the synchronous occurrence of algae (*Spirogyra* sp., Zygnemataceae, Type 229), the protozoa *Arcella* sp. and Neorhabdocoela oocytes is indicative of the existence of more humid and eutrophic conditions in the fen (Van Geel *et al.*, 1980–1981; Haas, 1996; Wilmshurst *et al*., 2003). Nevertheless, the occurrence of the mycorrhizal *Glomus* sp. (207) suggests that, even if more humid conditions arose during this period, the water-table levels remained low (Chmura *et al*., 2006). This could be explained by the existence of an irregular peat surface with hummocks and hollows.

This peat layer is characterised by the occurrence of gypsum and a geochemical anomaly showing high concentrations of metals (Fe, Ni, Cr and Cu). These metal anomalies may be the result of mining activities related to pyriteous Tertiary marls outcropping on the northern slope of the Cadí range. The oxidization of pyrites probably produced sulphuric acid, which may be responsible for the gypsum precipitation and metal mobility in the peat. These activities become the main human activity in the area during the eleventh century. In this regard, it is important to point out the establishment of late-Mediaeval iron forges in eastern Pyrenean and Pre-Pyrenean areas from the eleventh century onwards, as confirmed by the archaeological and documentary evidence (Izard, 1994; Sancho, 2002).

During this phase pine woodland recovery and the absence of wildfires contributed to slope stability. Moreover, the highest values of *Pinus* stomata and the existence of wood macro-remains in this peat layer indicate local pine woodland colonisation of fen hummocks (MacDonald, 2001).

This woodland recovery is related to the reduction in grazing activities, as evidenced by the minimum amounts of herbs and the fall in ruderal and nitrophilous indicators. This is also highlighted on a local scale by the decrease in the obligate coprophilous fungus *Sporormiella* sp. (Davis and Shafer, 2006) and other dung-related fungi. The increase of *Sordaria* sp., a non-strictly coprophilous fungi (Lundqvist, 1972), might here be related to the input of plant matter decay during this peat layer formation and the proximity of woodland to the fen. At lower altitudes the retreat of montane woodland is recorded even though cropping activities are negligible. Similar processes of farming and grazing reduction and woodland recovery have been already reported in southern Pyrenean ranges of the Cerdanya valley (Jalut, 1974).

This episode records the most similar landscape configuration to that prevailing today at Pradell, as recorded in environmental phase VI (Figure 6).

Phase III (AD 1100 ± 80 to 1600 ± 95: 133–72 cm). Late-Mediaeval cropping development with two economic and population crises between

Sediment during this environmental phase is characterised by massive dark brown silty clay with occasional reddish lamina and abundant charcoal particles. The sediment is mainly composed of quartz and philosilicates with low organic matter. A 2 mm thick lamina of light peat is recorded in the upper part of the phase. The lithological change towards the occurrence of colluvial deposits suggests an increase in soil erosion.

Arboreal pollen is dominated by pine with the occasional presence of birch and silver-fir, which disappears at AD 1240 (120 cm), while at lower altitudes deciduous woodland recovers. Subalpine woodland shows an oscillating pattern with regression periods also recording increases in macrocharcoal, which suggests the use of fire in woodland management. The recurrence of local fires is otherwise corroborated by the increase in fire-related fungi, such as G*elasinospora* sp. and the recording of *Neurospora* sp. (Blackford *et al*., 2006). In this respect, late-Mediaeval pine woodland exploitation has been archaeologically reported near the Pradell fen through the recording of two charcoal mounds dated to AD 1326 (ST 90) and AD 1342 (ST 82) (Euba, 2008) (Figure 1).

The larger expansion of herbs and juniper shrubs indicates an open landscape throughout this phase, a process which is especially notable from AD 1400 (Figure 4). The appearance of ruderal and nitrophilous taxa suggests the increase in grazing activities in this open landscape throughout the Mediaeval and Modern periods. This is in accordance with the development of transhumance linked to the Templar order in this part of the Cadí range from the late twelfth century (Sarobé, 1998). Moreover, late-Mediaeval transhumance is well documented in the eastern Pyrenees and its environmental impact at high altitudes has been recorded both archaeologically and through pollen analysis in the Cerdanya valley (Jalut, 1974; Rendu *et al*., 1995; Galop, 1998; Rendu, 2003). However, the slight increase in *Sporormiella* sp. and the low levels of other coprophilous fungi recorded indicate a modest local impact of such activities at Pradell, which is consistent with the absence of Mediaeval grazing structures near the fen. This may be explained by the fact that grazing activities were mainly regional and preferently located at the southern slope of the Cadí range, where the topography is more suitable for the extension of alpine pastures (Figure 1).

An important development in agricultural activities, mainly of annual crops such as cereal and rye, is recorded during the late Middle Ages, between AD 1138 and 1490. This is related to the feudalism process recorded in the Catalan Pyrenees from the tenth century onwards, which brought about an increase in population and arable land (Bonnassie, 1979; Salrach, 2004). The inclusion of the study area in this process is indicated by the establishment of a new town in the La Vansa valley during the thirteenth century (Gascón, 2007), a valley which had *c*. 200 inhabitants during the fourteenth century.

Despite the development of cropping, two main periods of farming retraction and woodland recovery are highlighted in the pollen diagram during the late Mediaeval and early Modern periods. The earlier one is recorded between AD 1240 (120 cm) and 1380 (105 cm) with minimum annual crops in AD 1329 and 1380 for Cerealia-type and *Secale*, respectively. Besides, the decline of Poaceae, Cichoroideae and *Plantago* suggests lower grazing pressure. This period may be related to the general demographic crisis that affected the whole Iberian Peninsula from 1348 and which can be linked to the spread of the Black Death, the existence of locust plagues and the smaller harvests during this time (Vilar, 1987; Fernández and Riera, 2004). The peak of *Pinus* percentage and concentration values recorded at AD 1329 (110 cm) shows woodland recovery as human pressure decreased.

The second cropping crisis is recorded in the upper part of this environmental phase, where Cerealia-type falls to its minimum and is replaced by the cultivation of olives, chestnuts and hemp between AD 1530 and 1580 (85–75 cm). This coincides with the last pine woodland recovery in the zone, the local nature of which is attested to by a peak of *Pinus* stomata (MacDonald, 2001) and a fall in macrocharcoal values. The reduction in human economic activities and woodland recovery has been observed in other Pyrenean areas at this time (Galop *et al.*, 2003; Mazier *et al*., 2009). All these facts suggest a decline in human activities in the area, which may have been triggered by the 'Little Ice Age'. In this respect, a colder phase of the LIA is registered by lichenometry between AD 1490 and 1558 in the neighbouring Madriu valley in Andorra (Mateo and Gómez, 2004), while a decrease in spring and summer temperatures has also been reported in the dendroclimatic series (Büntgen *et al.*, 2008). However, despite this decline in human activity, both written sources in AD 1575 (Gascón, 2009) and the reporting of a livestock enclosure at the Goleró site dated to AD 1568 (ST 47) underline the remaining presence of some cattle in the area.

The recorded Ni, Co and Cr peaks at AD 1520 (87 cm) and a major woodland clearance documented between AD 1400 and 1530 (100–90 cm) are in accordance with the documented establishment of two iron forges ('fargas') in the La Vansa and neighbouring valleys between AD 1495 and 1500 (Madurell, 1952) (Figure 1). Moreover, the recording of a charcoal mound (ST 84) dated to AD 1542 ± 90 corroborates pine woodland exploitation (Euba, 2008) for supplying charcoal to local iron forges (Figure 1).

Phase IV (AD 1600 ± 95 to 1900 ± 95: 72–18 cm). Towards a more complex and intensive high mountain socio-economic system

This phase begins with an 8 cm thick organic-rich light brown peat interbedded with brownish clays containing charcoal particles. The increase in organic matter content indicates a more stable water-table, probably as a consequence of moister conditions that are also evidenced by high lake water levels reported in the Pre-Pyrenees (Riera *et al.*, 2004). On top of the peat, reddish brown massive silt indicates slope activation, which is probably a consequence of human woodland clearances and a long period of temperature decrease (Büntgen *et al.*, 2008).

This organic level records a geochemical anomaly in metal content at AD 1612 (70 cm). The peaks of Pb, Cd, Cu, Co and Ca suggest the existence of metallurgical activities in the area, which are probably related to the iron forges dated to AD 1627 documented in the La Vansa valley (Gascón, 2009) and the neighbouring valleys for this period (Madurell, 1952). From this time on, low values in metal content are consistent with the documented abandonment of the iron forging activity in the La Vansa valley from the first half of the seventeenth century due to the exhaustion of the iron veins (Madurell, 1952; Gascón, 2009). Nevertheless, an isolated geochemical anomaly is recorded at AD 1780 (40 cm) with a small peak of Cr and Ni, which may be explained either by the regional iron forging activity still being carried out in the neighbouring valleys or by local metal surveys reported in written sources (Gascón, 2007). In this respect, the later written sources from the first half of the nineteenth century refer to the existence of iron production in the Cadí range (Madoz, 1845–1850). However, it must be considered that the signature and chronology of this metal anomaly is consistent with the geochemical signature of the well documented 'Laki dry fog' volcanic ash, which reached southern Europe and Spain in 1783 (Stothers, 1996; Guilbaud *et al.*, 2007).

An open landscape is recorded during this phase, with a retreat of pine woodland and the spread of shrub communities, mainly juniper and herbs. At lower altitudes, silver fir reappears and birch and *Quercus ilex*-type increase. Written sources report edicts to protect local woodland from tree felling and charcoal over-exploitation (Gascón, 2009). The continuation of and increase in some ruderal and nitrophilous taxa reported as local grazing indicators in mountain areas (Court Picon *et al.*, 2005; Mazier *et al.*, 2009), as well as high values of the coprophilous fungi *Sporormiella* sp., *Cercophora* sp. and *Podospora* sp., indicate the extension of grazing activities close to the Pradell fen. The recording of abundant modern pastoral structures at the Pradell and Goleró sites, dated through radiocarbon measurements (ST 30, ST 45, ST 46 and ST 48) and modern pottery finds (ST 02 and ST 31), are related to the expansion of transhumance activities. These are historically documented in the La Vansa valley from the seventeenth century (Gascón, 2007, 2009) and more widely in the eastern Pyrenees during modern times (Davasse *et al.*, 1997; Ros, 2004; Codina, 2005). Moreover, farming activities recover from AD 1600 onwards, mainly as orchards such as olive and chestnut. At this moment the continuous curve of *Cannabis*-type records the maximum expansion of this crop in the lower Pre-Pyrenees (Riera *et al.*, 2004). This period of increasing prosperity is well documented as the Catalan recovery after the long fourteenth to sixteenth century crisis, which also brought about a general demographic increase (Vilar, 1987; Gual, 2008) that is reflected in the local population curve (Figure 6).

Within this environmental phase, there was a significant shift in the NPP and pollen record during the second half of the eighteenth century. The whole NPP assemblage retreats, particularly fungal spores. This is synchronous with the specific decrease in most ruderal and nitrophilous pollen taxa and the general fall in cultivated pollen taxa, such as olive, chestnut, vines, Cerealia-type and rye. All this underlines a general decrease in human activity affecting not only the grazing practices previously recorded in the area, but also regional cropping activities. This period of economic stagnation has been historically reported in the Catalan region and Spain (Vilar, 1987; Ferrer, 2008) and coincides with a slight population decrease recorded between AD 1725 and 1790. These changes occur simultaneously with a colder phase within the LIA affecting the Pyrenees at this time (Creus and Saz, 1999).

From the end of the eighteenth century onwards, the recovery of coprophilous fungi, ruderal, nitrophilous and cultivated taxa testifies to the renewal of human activity in this area. This coincides with the significant increase in the local population, which reached its peak in AD 1860. This is consistent with the presence of three livestock enclosures dated to 1770 (ST 48), 1809 (ST 46) and 1810 (ST 45) at the Goleró site (Figure 1). The maintenance of an open landscape during this last period is testified to by the major presence of herbs and shrub pollen taxa and the remaining low pine percentage and absolute values. Moreover, although macrocharcoal values remained low during the whole episode, this tendency is accentuated from AD 1830. This may reflect the recorded felling of local woodland by the Spanish Royal Navy for shipbuilding during the last quarter of the eighteenth century and the authorities' banning of wood and charcoal exploitation (Pèlachs, 2004). At the end of this phase, a progressive decline in annual crops is evidenced during the last half of the nineteenth century, which coincides with the beginning of the abandonment of this highland area (Sabartés, 1998) (Figure 6).

Phase V (AD 1900 ± 95 to 1963: 18–7 cm). A progressive human abandonment of high mountain spaces

Between 18 and 7 cm, the Pradell sequence registers a 6 cm thick light brown organic-rich silt with vegetal fibres covered by 5 cm thick peat. Twentieth-century industrialisation is recorded by a general increase in metal content. Lead reaches its maximum levels at the end of this zone, just before the introduction of unleaded fuel.

During this zone an open landscape remains at high altitudes, as shown by the low percentage and concentration values of pine, while at lower altitudes deciduous oak woodland decreases. Juniper colonises these open landscapes, indicating the progressive abandonment of pastures, while the drop in most grazing pollen indicators and coprophilous fungi corroborates the general decline of grazing. This initial process of woodland recovery in the highlands is a consequence of land abandonment (Sabartes, 1998) in a context of milder climatic conditions (Büntgen *et al.*, 2008) that contributed to slope stabilisation and peat development.

Nevertheless, the continuation of woodland use is documented in the La Vansa valley, which was a centre for the production of turpentine and other medicinal products obtained from trees and shrubs in this highland area (Rodríguez, 2004). The disappearance of annual crops indicates that mountain cropping activities decreased in this context of human abandonment, whereas other crops, such as the olive, expand regionally on the lowland plains.

Phase VI (AD 1963 to the present day: 7–0 cm). Woodland colonisation and legal protection as the Cadí-Moixeró Natural Park

The uppermost part of the Pradell sequence is formed by dark brown peat with abundant vegetal fibres. The geochemistry shows the general increase in metal contamination related to the present-day industrial development. High values of calcite confirm the alkalinity of this fen.

A strong renewal of pine woodland at high altitudes is evidenced through the recording of the highest pine concentration values in the sequence and the reappearance of pine stomata. The recent woodland recovery is a consequence of the agro-pastoral abandonment of this mountain area during the twentieth century. This process was particularly dramatic in this part of the Pyrenees, as can be seen from the nearby towns, which lost 90% of their population at this time (Sabartés, 1998). Woodland recovery is also the result of preservation rules linked to the listing of this territory as a Natural Park in 1983.

Conclusions

The last 1500 years of environmental history recorded at the Pradell fen show that this highland area was subjected to multiple human practices, including mining and smelting, grazing, cropping, charcoal and turpertine production and tree felling. The main environmental phases related to the human management of the highlands are:

(1) From AD 525 to 850, relatively open woodland remains due to the existence of only moderate farming, grazing and mining activities that can be traced back to Roman times. From AD 850 to 950, more frequent fires as the result of farming and settlement stabilisation after the Christian conquest of the area.

(2) From AD 950 to 1100, mining was the main human activity with the development of the late-Mediaeval iron industry in the Pyrenees.

(3) From AD 1100 to 1600, a mixed system of highland human management is developed as part of the feudalism process. Phases of economic expansion resulted in local woodland clearances and crop expansion, whereas woodland recovery and farming retreat occurs during the 1330 and 1550 economic and demographic crises.

(4) From AD 1600 to 1900, maximum human impact at high altitudes and lowest woodland recovery is reported with the development of a mixed economy based on transhumance, farming, forestry and mining.

(5) From 1900 to 1963, the progressive abandonment of the area allowed the shrub colonisation of alpine grasslands.

(6) From 1963 to the present day, the subalpine woodland recovers as a result of human abandonment and the listing of the area as a Natural Park.

The palaeoenvironmental study of the Pradell fen corroborates the importance of grazing in causing a major environmental impact on the area from the seventeenth to the nineteenth centuries AD. This period largely influenced the present-day perception of the area as a traditional grazed landscape. However, the landscape shaping of this highland area is actually the result of a long-term interaction between many different human practices, as demonstrated by the palaeoenvironmental multiproxy analyses, the archaeological wealth and the historical archives. The multiplicity of human activities is particularly noteworthy during late Mediaeval and Modern times, when a mixed system of management and practices is reported, while some periods, such as the early Middle Ages, record the prevalence of mining and smelting as the main human activity undertaken in highlands.

This paper demonstrates the value of multiproxy analyses in the reconstruction of historical cultural landscapes in high mountain environments. The shortcomings of pollen in the characterisation of past human activities in high mountain areas, such as a large pollen source area, have been overcome by the use of proxies of more local origin such as NPPs, pine stomata, macrocharcoal particles and archaeological data from the vicinity of the studied site. Furthermore, geochemical and sedimentological analyses revealed mining and smelting activities which were poorly represented or not shown at all in the pollen record and had previously gone unreported in the study area. Historical and archaeological series also furnished key information in detailing human practices on a local and regional scale. In this regard, a noticeable consistence is recorded between the palaeoenvironmental indicators and the archaeological and historical data. The agreement between the historical and palaeoenvironmental archives is especially remarkable during the late-Mediaeval period, with the eleventh-century appearance of the Pyrenean iron industry, the feudal cropping expansion from the twelfth century, the fourteenth-century economic and population crisis and, during modern times, the sixteenth-century expansion of the modern iron industry, the seventeenth-century economic development and the recent human abandonment of the area. Archaeological and palaeoenvironmental results are otherwise especially consistent in recording modern transhumance activities between the sixteenth and the eighteenth centuries AD.

Finally, the crosschecking of proxies in the Pradell fen reinforces the chronological model constructed for this sequence and provides further evidence of the sensitivity of calcareous fens to changes in land use and their reliability for palaeoenvironmental studies.

Acknowledgements

The authors are grateful to Dr J.J. Blackford and to three anonymous referees for their helpful comments on earlier versions of this paper. We also thank Ll. Picornell for the macrocharcoal identification. This study received financial support from the Catalan Autonomous Government through an ACOM2007 funding.

References

Almenginder, J. and **Leete, J.** 1998: Peat characteristics and groundwater geochemistry of calcareous fens in the Minnesota River Basin, U.S.A. *Biochemistry* 43, 17–41.

Baraut, C. 1986: Els documents, dels anys 1093–1100, de l'Arxiu Capitular de la Seu d'Urgell. *Urgellia* 8, 7–150.

Behre, K.E. 1981: The interpretation of anthropogenic indicators in pollen diagrams. *Pollen et Spores* 13, 225–45.

Biagi, P. and **Nandris, J.,** editors 1994: *Highland zone exploitation in southern Europe*. Monografie di 'Natura Bresciana', 20.

Birks, H.J.B. and **Birks, H.H.** 1980: *Quaternary palaeoecology*. University Park Press.

Blackford, J.J. and **Innes, J.B.** 2006: Linking current environments and processes to fungal spore assemblages: surface NPM data from woodland environments. *Review of Palaeobotany and Palynology* 141, 179–87.

Blackford, J.J., Innes, J.B., Hatton, J.J. and **Caseldine, C.J.** 2006: Mid-Holocene environmental change at Black Ridge Brook, Dartmoor, SW England: a new appraisal based on fungal spore analysis. *Review of Palaeobotany and Palynology* 141, 189–201.

Bonnassie, P. 1979: *Catalunya mil anys enrere. Creixement econòmic i adveniment del feudalisme a Catalunya de mitjan segle X al finals del segle XI*. Edicions 62.

Boyer, M.L.H. and **Wheeler, B.D.** 1989: Vegetation patterns in spring-fed calcareous fens: calcite precipitation and constraints on fertility. *The Journal of Ecology* 77, 597–609.

Brugiapaglia, E., Beaulieu, J.L., Guiot, J. and **Reille, M.** 1998: Transect de pluie pollinique et étagement de la végétation dans le Massif du Taillefer (Isère, France). *Géographie Physique et Quaternaire* 52, 1–10.

Büntgen, U., Frank, D., Grudd, H. and **Esper, J.** 2008: Long-term summer temperature variations in the Pyrenees. *Climate Dynamics* 31, 615–31.

Camarero, L., Masqué, P., Devos, W., Ani-Ragolta, I., Catalán, J., Moor, H.C., Pla, S. and **Sánchez-Cabeza, J.A.** 1998: Historical variations in lead fluxes in the Pyrenees (Northeast Spain) from a dated lake sediment core. *Water, Air, and Soil Pollution* 105, 439–49.

Carcaillet. C., Bouvier, M., Fréchette, B., Larouche, A.C. and **Richard, P.J.H.** 2001: Comparison of pollen-slide and sieving methods in lacustrine charcoal analyses for local and regional fire history. *The Holocene* 11, 467–76.

Carreras, J., Carrillo, E., Font, X., Ninot, J. M., Soriano, I. and **Vigo, J.** 1995: Vegetation of the Pre-Pyrenean ranges between the rivers Segre and Llobregat (Southeastern Pyrenees). I- Forest communities (Woods and hedges). *Ecologia Mediterranea* 21, 21–73.

Chmura, G.L., Stone, P.A. and **Ross, M.S.** 2006: Non-pollen microfossils in Everglades sediments. *Review of Palaeobotany and Palynology* 141, 103–19.

Codina, O. 2005: *De fer et de laine. Les vallées andorranes du XVIe au XIXe siècle*. Presses Universitaires de Perpignan.

Court-Picon, M., Buttler, A. and **de Beaulieu, J.L.** 2005: Modern pollen–vegetation relationships in the Champsaur valley (French Alps) and their potential in the interpretation of fossil pollen records of past cultural landscapes. *Review of Palaeobotany and Palynology* 135, 13–39.

Covelli, S. and **Fontolan, G.** 1997: Application of a normalization procedure in determining regional geochemical baselines. *Environmental Geology* 30, 34–45.

Creus, J. and **Saz, M.A.** 1999: Estudio de la variabilidad climática del último milenio a partir de series de temperatura y precipitaciones reconstruidas en el noreste español. In Raso, J.M. and Martin-Vide, J., editors, *La climatologia española en los albores del s. XXI*. Asociación Española de Climatologia, 155–64.

Davasse, B., Galop, D. and **Rendu, C.** 1997: Paysages du Néolithique à nos jours dans les Pyrénées de l'Est d'après l'écologie historique et larchéologie pastorale. La dynamique des paysages protohistoriques, antiques, médiévaux et modernes. *17èmes rencontres internationales dArchéologie et d´Histoire d´Antibes*. Éditions APDCA-Sophia Antipolis, 577–99.

Davis, O.K. and **Shafer, D.** 2006: Sporormiella fungal spores, a palynological means of detecting herbivore density. *Palaeogeography, Palaeoclimatology, Palaeoecology* 237, 40–50.

Dean, W.E.JR.J. 1974: Determination of carbonate and organic matter in calcarcous sediments and sedimentary rocks by loss on ignition: comparison with other methods. *Journal of Sedimentary Petrology* 44, 242–48.

Dearing, J.A., Battarbee, R.W., Dikau, R., Larocque, I. and **Oldfield, F.** 2006: Human–environment interactions: learning from the past. *Regional Environmental Change* 6, 115–23.

Ejarque, A. and **Orengo, H.A.** 2009: Legacies of change: the shaping of cultural landscapes in a marginal Mediterranean range, Garraf Massif, North-eastern Spain. *Oxford Journal of Archaeology* 28, 425–40.

Euba, I. 2008: *Análisis antracológico de estructuras altimontanas en el Valle de La Vansa-Sierra del Cadí (Alt Urgell) y en el Valle del Madriu (Andorra): explotación de recursos forestales del Neolítico a la época moderna*. Universitat Rovira i Virgili, online, http:/www.tdx.cat/TDX-1121108-124416, accessed 19 March 2009.

Faegri, K., Kaland, P.E. and **Krzywinski, K.,** editors 1989: *Textbook of pollen analysis. 4th edition*. The Blackburn Press.

Fernández, J. and **Riera, A.** 2004: La crisis econòmica i social al camp. In Giralt, E. and Salrach, J.M., coordinators, *Història Agraria dels Països Catalans, v.2, Edat Mitjana*. Universitat de Barcelona, 119–79.

Ferrer, L. 2008: El segle XVIII: culminació i final d´un model de creixement econòmic agrari. In Giralt, E. and Salrach, J.M., coordinators, *Història Agraria dels Països Catalans, v.3, Edat Moderna*. Universitat de Barcelona, 55–90.

Galop, D. 1998: *La forêt, l'homme et le troupeau dans les Pyrénées. 6000 ans d'histoire de l'environnement entre Garonne et Méditerranée. Contribution palynologique*. GEODE-Laboratoire d'écologie terrestre-Framespa.

—— 1999: Le parchemin et le pollen: la Cerdagne médiévale, de l'archive écrite à l'archive naturelle. In *Les sociétés méridionales à l'âge féodal. Hommage à Pierre Bonnassie*. CNRS, Université de Toulouse-le-Mirail, 35–43.

Galop, D., Mazier, F., López-Saez, J.A. and **Vannière, B.** 2003: Palynologie et histoire des activités humaines en milieu montagnard. Bilan provisoire des recherches et nouvelles orientations méthodologiques sur le versant nord des Pyrénées. *Archéologie du Midi Médiéval* 21, 159–70.

Gascón, C. 2007: Resultat de l'estudi de les fonts documentals. In Palet, J.M, editor, *Sol.licitut d'Ajut per al desenvolupament de projectes d'abast comarcal-ACOM 2004. Memòria final de l'activitat de recerca realitzada*. Agència de Gestió d'Ajuts Universitaris i de Recerca, 35–74.

—— 2009: Resultat de l'estudi de les fonts documentals. In Riera, S., editor, *Sol.licitut d'Ajut per al desenvolupament de projectes d'abast comarcal-ACOM 2007. Memòria final de l'activitat de recerca realitzada*. Agència de Gestió d'Ajuts Universitaris i de Recerca, 11–13.

Gómez, A. and **Esteban, A.** 1993: Análisis polínico de la turbera de la Feixa (La Màniga, Cerdanya, 2.150 m). Evolución del paisaje. In Fumanal, M.P. and Bernabeu, J., editors, *Estudios sobre Cuaternario. Medios sedimentarios. Cambios ambientales. Hábitat humano*. Universitat de València, 185–90.

González-Sampériz, P., Valero-Garces, B.L., Moreno, A., Jalut, G., Garcia-Ruiz, J.M., Marti-Bono, C., Delgado-Huertas, A., Navas, A., Otto, T. and **Dedoubat, J.J.** 2006: Climate variability in the Spanish Pyrenees during the last 30,000 yr revealed by the El Portalet sequence. *Quaternary Research* 66, 38–52.

Grimm, E. 1987: CONISS: a Fortan 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers and Geosciences* 13, 13–35.

Gual, V. 2008: El punt de partida de l'agricultura moderna. De la Sentència Arbitral de Guadalupe i les Germanies a la crisi de finals del cinc-cents. In Giralt, E. and Salrach, J.M., coordinators, *Història Agrària dels Països Catalans, v.3, Edat Moderna*. Universitat de Barcelona, 13–30.

Guilbaud, M.N., Blake, S., Thordarson, T. and **Self, S.** 2007: Role of syn-eruptive cooling and degassing on textures of lavas from the AD 1783–1784 Laki eruption, South Iceland. *Journal of Petrology* 48, 1265–94.

Guiter, F., Andrieu-Ponel, V., Digerfeldt, G., Reille, M., de Beaulieu, J.L. and **Ponel, P.** 2005: Vegetation history and lake-level changes from the Younger Dryas to the present in the Eastern Pyrenees (France): pollen, plant macrofossils and lithostratigraphy from Lake Racou (2000 m a.s.l.). *Vegetation History and Archaeobotany* 14, 99–118.

Haas, J.N. 1996: Neorhabdocoela oocytes – palaeoecological indicators found in pollen preparations from Holocene freshwater lake sediments. *Review of Palaeobotany Palynology* 91, 371–82.

Hansen, B.C.S. 1995: Conifer stomate analysis as a paleoecological tool: an example from the Hudson Bay lowlands. *Canadian Journal of Botany* 73, 244–52.

Heiri, O., Lotter, A.F. and **Lemcke, G.** 2001: Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology* 25, 101–10.

Izard, V. 1994: Cartographie successive des entrerprises métallurgiques dans les Pyrénées nor-catalanes; support préliminaire à l'étude éco-historique des forêts charbonnées. *Archéologie du Midi médiéval* 12, 115–29.

Jalut, G. 1974: Évolution de la végétation et variations climatiques durant les quinze derniers millenaires dans l'extremité orientale des Pyrénées. PhD Thesis, Université Paul Sabatier.

Jalut, G., Monserrat, J., Fontugne, M., Delibrias, G., Vilaplana, J.M. and **Julià, R.** 1992: Glacial to interglacial vegetation changes in the Northern and Southern Pyrenees: deglaciation, vegetation cover and chronology. *Quaternary Science Reviews* 11, 449–80.

Jouffroy-Bapicot, I., Pulido, M., Baron, S., Galop, D., Monna, F., Lavoie, M., Ploquin, A., Petit, C., de Beaulieu, J.L. and **Richard, H.** 2006: Environmental impact of early palaeometallurgy: pollen and geochemical analysis. *Vegetation History and Archaeobotany* 16, 251–58.

Juggins, S. 1991: *C2 data analysis vs.1.4.2*. University of Newcastle.

Kober, B., Wessels, M., Bollhöfer, A. and **Mangini, A.** 1999: Pb isotopes in sediments of Lake Constance, Central Europe constrain the heavy metal pathways and the pollution history of the catchment, the lake and the regional atmosphere. *Geochimica et Cosmochimica Acta* 9, 1293–303.

Lotter, A.F., Appleby, B.G., Bindler, R., Dearing, J.A., Grytnes, J.A., Hofmann, W., Kamenik, C., Lami, A., Livingstone, D.M., Ohlendorf, C., Rose, N. and **Sturm, M.** 2002: The sediment record of the past 200 years in a Swiss high-alpine lake: Hagelseewli (2339 m a.s.l.). *Journal of Paleolimnology* 28, 111–27.

Lundqvist, N. 1972: Nordic Sordariaceae s. lat. *Symbolae Botanicae Upsalienses* 20, 1–374.

Luo, S. and **Ku, T.L.** 1991: U-series isochron dating: a generalized method employing total-sample dissolution. *Geochimica et Cosmochimica Acta* 55, 555–64.

MacDonald, G.M. 2001: Conifer stomata. In Smol, J.P., Birks, H.J.B. and Last, W.M., editors, *Tracking environmental change using lake sediments, 3: terrestrial, algal and silicaceaous indicators*. Kluwer, 33–47.

Madoz, P. 1845–1850: *Diccionario geográfico-estadístico-histórico de España y sus posesiones de Ultramar. Tomo I to XVI.* Curial. Ed. Facsímil.

Madurell, J.M. 1952: Las fargas pirenaicas. *Pirineos* 25, 545–55.

Mateo, M. and **Gómez, A.** 2004: La Pequeña Edad del Hielo en Andorra: episodios morfogenéticos y su relación con la producción de cereales en Europa. *Boletín de la Sociedad Española de Historia Natural (Sección Geológica)* 99, 173–83.

Mazier, F., Galop, D., Gaillard, M.J., Rendu, C., Cugny, C., Legaz, A., Peyron, O. and **Buttler, A.** 2009: Multidisciplinary approach to reconstructing local pastoral activities – an example from the Pyrenean Mountains (Pays Basque). *The Holocene* 19, 171–88.

Miras, Y., Ejarque, A., Riera, S., Palet, J. M., Orengo, H. and **Euba, I.** 2007: Dynamique holocène de la végétation et occupation des Pyrénées andorranes depuis le Néolithique ancien, d'après l'analyse pollinique de la tourbière de Bosc dels Estanyons (2180m, Vall del Madriu, Andorre). *Comptes rendus Palevol* 6, 291–300.

Moe, D. and **Hjelle, K.L.** 1999: Mesolithic human adaptation to changing alpine/subalpine vegetation in the Central and Eastern Alps based on vegetational historical study from Val Febbraro, Spluga Valley (Italy). *Universitätsforschung zur prähistorischen Archäologie* 55, 207–14.

Montserrat, J. 1992: *Evolución glaciar y postglaciar del clima y la vegetación en la vertiente sur del Pirineo: estudio palinológico*. Monografías del Instituto Pirenaico de Ecología 6.

Moore, P.D., Webb, J.A. and **Collinson, M.E.** 1991: *Pollen analysis*. 2nd edition. Blackwell Scientific Publications.

Palet, J.M., Ejarque, A., Miras, Y., Riera, S., Euba, I. and **Orengo, H.A.** 2007: Formes d'ocupació d'alta muntanya a la vall de la Vansa (Serra del Cadí-alt Urgell) i a la vall del Madriu-Perafita-Claror (Andorra): estudi diacrònic de paisatges culturals pirinencs. *Tribuna d'Arqueologia* 2006–2007, 229–53.

Palet, J.M., Orengo., H.A., Ejarque, A., Euba, I., Miras, Y. and **Riera, S.** 2009: Formas de paisaje de montaña y ocupación del territorio en los Pirineos orientales en época romana: estudios pluridisciplinares en el valle del Madriu-Perafita-Claror (Andorra) y en la Sierra del Cadí (Cataluña). In Proceedings of the 17th International Congress of Classical Archaeology (Roma 22–26 Septiembre 2008. *Bollettino di Archeologia* on-line, in press.

Pèlachs, A. 2004: *Deu mil anys de geohistòria ambiental al Pirineu central català. Aplicació de tècniques paleogeogràfiques per a l'estudi del territori i del paisatge a la Coma de Burg i a la Vallferrera*. Universitat Autònoma de Barcelona, online, http:/www.tdx.cat/TDX-0119105-162806, accessed 12 February 2009.

Pla, S. and **Catalan, J.** 2005: Chrysophyte cysts from lake sediments reveal the submillennial winter/spring climate variability in the northwestern Mediterranean region throughout the Holocene. *Climate Dynamics* 24, 263–78.

Reille, M. 1992: *Pollen et spores d'Europe et d'Afrique du nord*. Laboratoire de Botanique historique et Palynologie, Université d'Aix-Marseille III.

Reille, M. and **Lowe, J.J.** 1993: A re-evaluation of the vegetation history of the eastern Pyrenees (France) from the end of the last glacial to the present. *Quaternary Science Reviews* 12, 47–77.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J. and **Weyhenmeyer, C.E.** 2004: IntCal04 terrestrial radiocarbon age calibration, 26–0 ka BP. *Radiocarbon* 46, 1029–58.

Rendu, C. 2003: *La montagne d'Enveig. Une estive pyrénéenne dans la longue durée*. Trabucaire.

Rendu, C., Campmajó, P., Davasse, B. and **Galop, D.** 1995: Habitat, environnement et systèmes pastoraux en montagne: acquis et perspectives de recherques à partir de l'étude du territoire d'Enveig. In *Cultura i medis de la prehistòria a l'Edat Mitjana, Xe col.loqui internacional d'arqueologia de Puigcerdà, homenatge a Jean Guilaine*. Institut d'Estudis Ceretans, 661–708.

Riera, S., Wansard, G. and **Julià, R.** 2004: 2000-yr environmental history of a karstic lake in the Mediterranean Pre-Pyrenees: the Estanya lakes (Spain). *Catena* 55, 293–324.

Rodríguez, M. 2004: Les trementinaires. *Medicina naturista* 7, 339–50.

Ros, I. 2004: *La transhumància andorrana al llarg del segle XX*. Editorial Alta Fulla.

Rose, N. 1999: The spatial and temporal distributions of Spheroidal Carbonaceous Fly-Ash Particles (SCP) in the sediment records of European mountain lakes. *Water, Air, and Soil Pollution* 113, 1–32.

Sabartés, J.M. 1998: *Població i territori a l'Alt Pirineu Català. Anàlisi demogràfica de les comarques de l'Alt Urgell, Alta Ribagorça, Cerdanya, Pallars Jussà, Pallars Sobirà i Vall d'Aran*. Garsineu edicions.

Salrach, J.M. 2004: Època prefeudal (segles VIII–X) i canvi feudal (segles XI–XII). In Giralt, E. and Salrach, J.M., coordinators, *Història Agraria dels Països Catalans, v.2, Edat Mitjana.* Universitat de Barcelona, 15–44.

Sancho, M. 2002: Recerca arqueològica en un establiment siderúrgic del segle XI: el jaciment de la Fabregada (Sant Esteve de la Sarga, Pallars Jussà). *Tribuna d'Arqueologia* 1998–1999, 287–304.

Sarobé, R. 1998: *Col.lecció diplomàtica de la Casa del Temple de Gardeny (1070–1200).* Fundació Noguera.

Stockmarr, J. 1971: Tablets with spores used in absolute pollen analysis. *Pollen et spores* 13, 615–21.

Stothers, R.B. 1996: The great dry fog of 1783. *Climatic Change* 32, 79–89.

van Geel, B. 1986: Application of fungal and algal remains and other microfossils in palynological analyses. In Berglund, B.E., editor, *Handbook of Holocene palaeoecology and palaeohydrology*. Wiley, 497–505.

—— 2001: Non-pollen palynomorphs. In Smol, J.P., Birks, H.J.B. and Last, W.M., editors, *Tracking environmental change using lake sediments, 3: terrestrial, algal and silicaceaous indicators*. Kluwer, 99–119.

van Geel, B. and **Aptroot, A.** 2006: Fossil ascomycetes in Quaternary deposits. *Nova Hedwig*ia 82, 313–29.

van Geel, B., Bohncke, S.J.P. and **Dee, H.** 1980–1981: A palaeoecological study of upper Late Glacial and Holocene sequence from 'De Borchert', The Netherlands. *Review of Palaeobotany and Palynology* 31, 367–448.

Vergés, J., Muñoz, J.A. and **Martínez, A.** 1992: South Pyrenean fold-and-thrust belt: role of foreland evaporitic levels in thrust geometry. In McClay, K., editor, *Thrust tectonics*. Chapman and Hall, 255–64.

Vigo, J., Soriano, J., Carreras, J., Aymerich, P., Carrillo, E., Font, X., Masalles, R.M. and **Ninot, J.M.** 2003: *Flora del Parc Natural del Cadí-Moixeró i de les serres veïnes*. Monografies del Museu de Ciències Naturals, 1.

Vigo, J., Carreras, J. and **Ferré, A.** 2006: *Cartografia dels habitats a Catalunya. Manual d'interpretació Departament de Medi Ambient i Habitatge*. Generalitat de Catalunya.

Vilar, P. 1987: *Catalunya dins l'Espanya moderna: recerques sobre els fonaments econòmics de les estructures nacionals*. Edicions 62.

Walsh, K. and **Richer, S.** 2006: Attitudes to altitude: changing meanings and perceptions within a 'marginal' Alpine landscape – the integration of palaeoecological and archaeological data in a high altitude landscape in the French Alps. *World Archaeology* 38, 436–54.

Wilmshurst, J.M., Wiser, S.K. and **Charman, D.J.** 2003: Reconstructing Holocene water tables in New Zealand using testate amoebae: differential preservation of tests and implications for the use of transfer functions. *The Holocene* 13, 61–67.