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Holocene vegetation changes in NW Iberia revealed by anthracological and palynological records from a colluvial soil

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Abstract: Macroscopic charcoal, pollen and non-pollen palynomorphs were isolated from a colluvial soil located on a small hill in Campo Lameiro (NW Spain) in order to elucidate the vegetation history of the area and its relation to fire and human activities. The presence of macroscopic charcoal throughout the 2.10 m thick soil (42 samples) is evidence of frequent fires during the last *c*. 6300 years. The charcoal record was dominated by *Quercus* (probably *Q. robur*), Ericaceae (probably *Arbutus unedo* and *Erica arborea*) and Fabaceae (mainly *Genista* type). Abrupt changes in the charcoal assemblage are less explicit in the pollen sequence, probably as a result of pollen inflow from the downhill surroundings of the study site. Combined results indicated that the original oak woodland was gradually replaced by pyrophytic shrubs (Ericaceae and Fabaceae) as a result of fire recurrence. Non-pollen palynomorphs strongly suggested that vegetation was deliberately ignited by past human societies to facilitate grazing. No evidence of local agricultural practices was found. Episodes of accelerated shrubland expansion occurred *c*. 6000–5500 cal. BP, *c*. 4000–3500 cal. BP and *c*. 1700 cal. BP, the latter of which caused the definitive settlement of shrublands dominated by Ericaceae and Fabaceae which are nowadays widespread in NW Iberia.

Key words: Charcoal analysis, pollen, non-pollen palynomorphs, fire, vegetation dynamics, NW Iberia.

Introduction

The formation of open-cultural landscapes as the outcome of burning vegetation by prehistoric societies has been studied extensively, especially in Europe (Clark *et al.*, 1989; Tinner *et al.*, 1999; Santos *et al.*, 2000; Carcaillet *et al.*, 2002; Ruddiman, 2003; Gerlach *et al.*, 2006; Hajdas *et al.*, 2007). However, in Galicia (NW Spain), few studies have been undertaken to relate human activities to the fire regime and formation of the present-day landscape, even though it is well-known that fire has played an essential role in the landscape evolution during the Holocene (Bouhier, 1979; Martínez Cortizas, 2000; Fábregas Valcarce *et al.*, 2003). Fire, climate change, human activities and vegetation dynamics form a complex cycle of cause and effect that is difficult to disentangle (Vannière *et al.*, 2008; Cordova *et al.*, 2009).

In this paper, we attempt to discern the evolution of the local and regional Holocene vegetation in NW Iberia under the impact of the human population. For this purpose, wood-charcoal and pollen analyses have been carried out in the colluvial soil of PRD-2, in which charcoal accumulations have occurred as a result of recurrent fires. The PRD-2 profile represents the last *c*. 6300 years of soil accumulation (Costa Casais *et al.*, 2009). Knowledge on landscape evolution and human activities in this region is paramount because the area harbours one of the largest concentrations

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of rock art in the NW Iberian Peninsula which is bound to become a major tourist attraction after the completion of a museum (http://www.campolameiro.com/centro_inter_cast.html).

In the NW Iberian Peninsula, organic matter-rich colluvial soils (Atlantic rankers) are widespread (Carballas *et al.*, 1978). Environmental proxies obtained from such soils can be used for reconstructing past landscapes and their evolution (Kalis *et al.*, 2003). Pollen and charcoal are two such proxies which enable to us to establish the relationship that links fire, human activity and vegetation change. Such a combination of tools also provides information on the spatial scale of environmental change. While macroscopic charcoal generally reflects local wood burning events, pollen analyses might provide a relatively complete image of vegetation dynamics on a more regional scale, including unburned areas (Carrión, 2005; Colombaroli *et al*., 2008; di Pasquale *et al.*, 2008). Unlike the pollen analysis, the charcoal record lacks information on grasses, and often on sedges and ferns, because they have either been completely reduced to ashes or are difficult to identify on the basis of their anatomy (Emery-Barbier and Thiébault, 2005). Differential production, transport and degradation rates of pollen and charcoal for the different species introduce a bias into both data sets and further discrepancies appear among them (Havinga, 1984; Figueiral and Mosbrugger, 2000; Scott *et al.*, 2000). Consequently, palynological and anthracological records must be interpreted and compared with caution.

Apart from determining the composition of vegetation by means of pollen types, palynological studies may provide information on other site conditions using non-pollen palynomorphs (NPPs). Most NPPs are locally produced and may be related to a specific soil trophic status (eg, Zygnemataceae, Cyanobacteria), to the presence of specific soil components (*Chaetomium*/charcoal, *Sordaria* and *Sporormiella*/animal excrements, etc.), or to geomorphological processes (*Spyrogira*/flooding, *Glomus*/soil erosion) (López Sáez *et al.*, 1998; van Geel, 2001). Therefore, NPPs can be used in combination with pollen and charcoal records to obtain a deeper understanding of vegetation dynamics and environmental conditions.

In this sense, this paper aims to (1) understand the vegetation dynamics of Campo Lameiro and the role of fire therein and (2) identify human activities and their link to vegetation and the fire history since the mid Holocene.

Geographical and archaeological setting

Campo Lameiro is located in a subcoastal area, 25 km east from the Atlantic Ocean in the temperate region of the NW Iberian Peninsula (Figure 1a). Here the climate is characterised as mild and humid, with mean annual temperatures of 15°C (9°C in winter and 21°C in summer) and a mean annual precipitation of 1200 mm (concentrated in autumn and winter) (Martínez Cortizas and Pérez Alberti, 1999). Despite the high annual rainfall, the vegetation of this area is susceptible to ignition because of the dry summer period. Current vegetation is a mosaic of shrubs (heather, gorse and broom), trees (pine, eucalyptus and oak), ferns (common bracken) and grasses.

The Paredes section (PRD) in the Rock Art Park of Campo Lameiro (42°32′47.86″N; 8°31′40.42″W) is located on a hill called *Monte Paradela* (190–330 m a.s.l.), which is surrounded by several small streams. Therefore, it is isolated from sediment pathways other than those on the hill itself (Figure 1b,c). In the summer/autumn of 2008, a series of archaeological structures, which probably evidence (temporary) small-scale human settlements, have been excavated from the museum's construction site (Figure 1c). Nevertheless, the archaeological function of the petroglyphs and

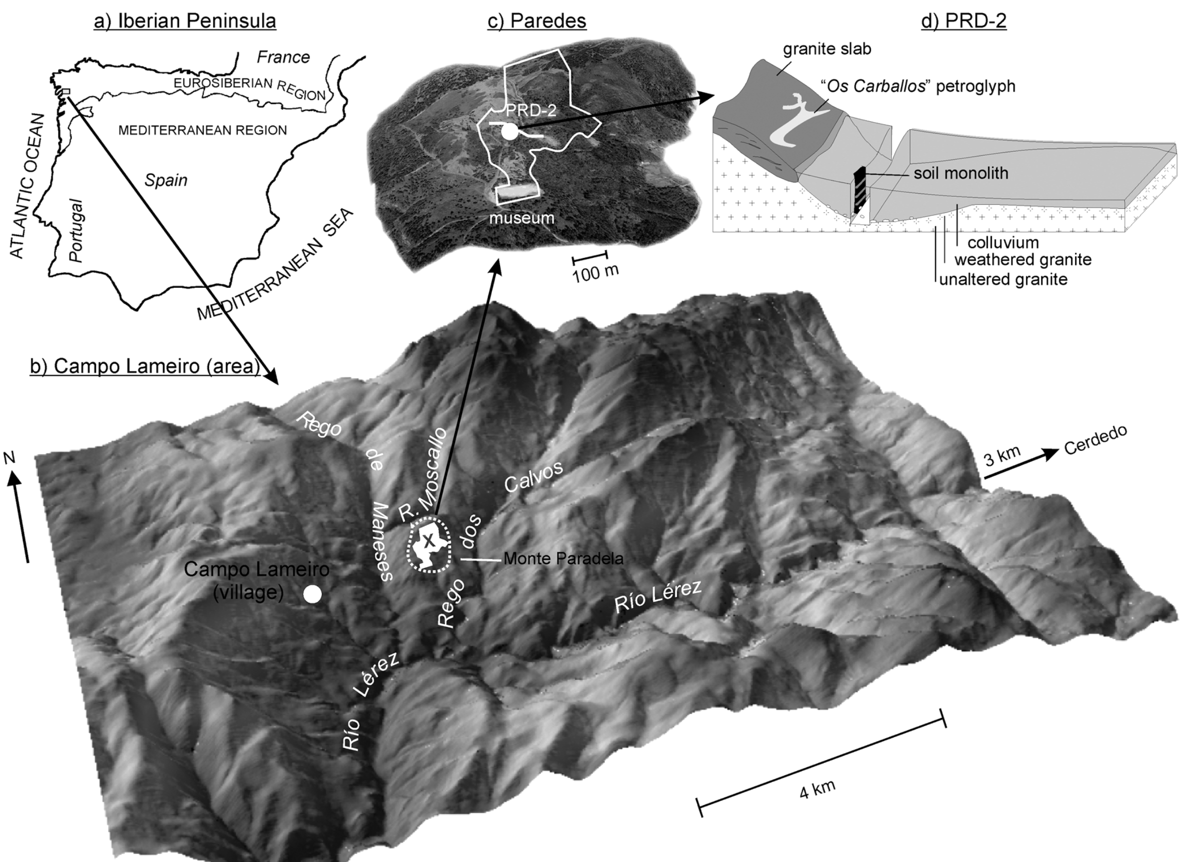

Figure 1 Location of the study area (a–c) and sampling site (d). Greyscale on 3D plot represents altitudes from 100 to 508 m a.s.l.

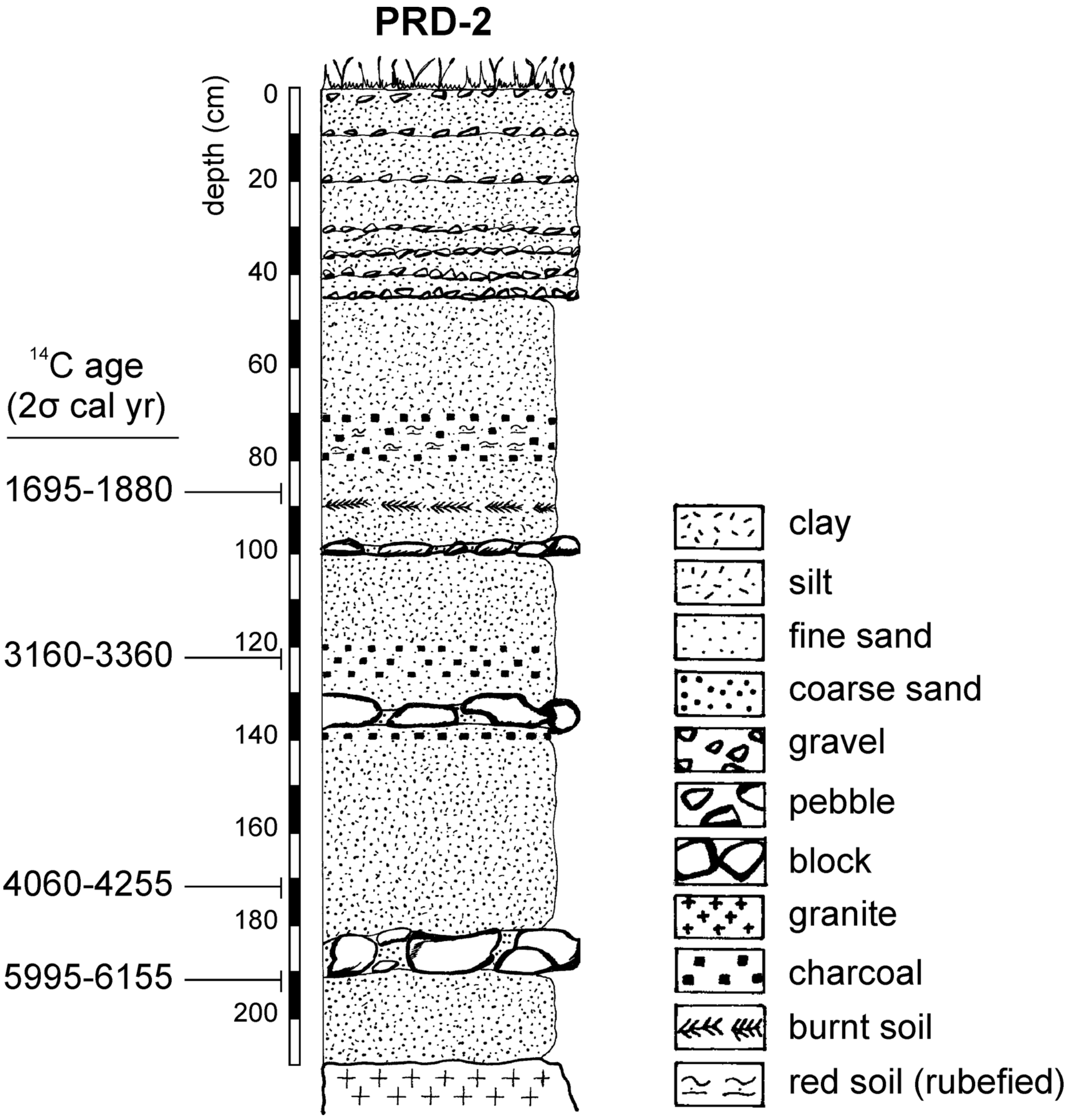

Figure 2 PRD-2 soil profile with radiocarbon ages (drawing courtesy of Manuela Costa Casais)

the potential housing structures are poorly understood. The almost complete lack of archaeological materials (eg, pottery) obtained from the area suggests that only a small number of humans had settled there and that they did not inhabit the site over long continuous periods.

Material and methods

The soil under study (PRD-2) is one of a series of five profiles obtained from the Paredes section in Campo Lameiro (Figure 1d). Located at an altitude of 310 m a.s.l., it is next to a rock art panel called '*Os Carballos*' (Santos Estévez, 2005). In 2003, a trench was dug in the colluvial sediment next to this petroglyph. A 2.10 m thick soil monolith was collected from this trench (Figure 1d) and was cut into 5 cm intervals to obtain 42 soil samples (Figure 2). No evidence of either fireplaces or other domestic activities was found during the excavation of PRD-2. The soil material (including charcoal) had probably accumulated through natural sedimentation, since we have no evidence of eg, fireplaces or other domestic activities. For this reason, it is considered an 'off-site' record. This soil is classified as haplic Umbrisol International Union of Soil Sciences–ISRIC World Soil Information–FAO (IUSS, 2006). In Western Europe, such soils are traditionally referred to as Atlantic rankers and they generally develop in humid areas under temperate conditions with high primary production and strong weathering of granite.

Radiocarbon ages of four soil organic matter samples obtained by the standard acid-alkaline-acid extraction protocol of the Ångstrom Laboratory (Uppsala University, Sweden) are shown in Figure 2. ^{14}C dates were calibrated using CALIB 5.0.1 (Stuiver and Reimer, 1993). It is quite unlikely that the buried layers of PRD-2 received significant amounts of fresh organic matter because the soil is rich in poorly crystalline Al phases, which limits organic matter mobility, and also because humic acids were used for ^{14}C measurements (lacking fresh organic matter). This was confirmed by the molecular characterisation of the organic matter using the pyrolysis-GC/MS method (Kaal *et al.*, 2008a, b). Therefore, the ^{14}C ages obtained are unlikely to be biased by rejuvenation. A comparison made with ^{14}C dated samples from other soils in Campo Lameiro indicates that the surface of PRD-2 is erosive and roughly 200–600 years old.

Macroscopic charcoal (> 2 mm) was separated from the soil samples by wet sieving and was weighed after drying. The botanical identification of charcoal was done using a metallurgical microscope at a magnification of between 100 and 1000

(Vernet, 1973; Vernet *et al.*, 1979). The anatomical patterns observed were compared with a reference collection of carbonised wood, anatomy atlases and specialised bibliography (Metcalfe, 1960; Metcalfe and Chalk, 1950; Greguss, 1955, 1959; Jacquiot, 1955; Jacquiot *et al.*, 1973; Schweingruber, 1978, 1990) so that charcoal fragments could be identified to the species, genus or family level. When a higher magnification was required, charcoal was examined with a scanning electron microscope (SEM). A total of 2063 fragments have been identified. Although the mass of the fragments is sometimes used to express relative species abundance (eg, Carcaillet and Thinon, 1996), in this paper we used the number of fragments as proposed by Delhon (2006).

Other dendrological features (growth-rings curvature, radial cracks and vitrification) were examined under low magnification (Marguerie and Hunot, 2007). The degree of ring curvature was determined for large charcoal particles (> 5 mm radius and > 3–4 mm tangential width) by estimating the parallelism of rays. The growth-rings of these particles were classified as being weakly, intermediately or strongly curved. This classification enables the estimation of the maturity of the plant when it was burnt. A large proportion of charcoal with strongly curved rings reflects the burning of small calibre wood (Marguerie and Hunot, 2007). The presence or absence of vitrified elements and radial cracks in the charcoal was denoted qualitatively. Radial cracks in charcoal can be, among other causes, an indicator of the burning of green wood, which can be accounted for by rapid dehydration and conflagration (Théry-Parisot, 2001). Vitrification results in a gradual fusion of cell walls which creates a glass-like surface and a low pore volume of the charcoal (Pulido-Novicio *et al.*, 2001), thus making botanical identification difficult. The factors which cause this phenomenon are still a matter of debate, but most authors agree that it generally occurs when one of the following fire parameters are met: (1) high temperature (Fabre, 1996; Tardy, 1998), (2) high moisture content of the burnt wood (Thinon, 1992) and (3) burning of green wood in general (Scheel-Ybert, 1998).

Pollen and NPPs were counted using the same volume of preparation (5 g/sample). Pollen grains were extracted using the classical method of concentration in a heavy liquid (Thoulet solution, d=2) after treatment with HCl and HF (Faegri and Iversen, 1989). The pollen results are provided as the percentage of the total pollen sum (approximately 500) accounted for by a given pollen taxon. The Cyperaceae, ferns and NPPs were not added to the total pollen sum, although their frequencies are expressed as percentages of the pollen sum (van Geel *et al.*, 1981). Pollen diagrams were plotted in Tilia and TiliaGraph 2.0 (Grimm, 1992). Here we provide a summary of the results of the pollen analysis. For a more detailed description of the pollen and NPP records, please refer to López Sáez *et al.* (2009).

Results and discussion

Charcoal

Macroscopic charcoal was present in all the samples, which is a sign of frequent burning on a local scale (Clark *et al*., 1998; Blackford, 2000; Gardner and Whitlock, 2001; Lynch *et al*., 2004) for the past *c*. 6300 years. The taxonomical diversity of the charcoal was poor: only 13 taxa were identified (Figure 3), four of which (*Erica* sp., Fabaceae, deciduous *Quercus* and *Arbutus unedo*) accounted for 98±5% of the charcoal (mean and standard deviation for 41 samples). Although some samples, particularly those from the top of the soil, provided only a small number (20–30) of identified charcoal fragments (see Appendix 1), most spectra are statistically meaningful as they have been tested in 'saturation curves' (Chabal, 1997) (Figure 4). In addition, we found no significant relationship between the amount of charcoal fragments analysed and the number of taxa identified.

Heathers were the most frequently observed taxonomical group (53±37%). According to the ray width criteria proposed by Queiroz and Van der Burgh (1989), the heathers in PRD-2 mostly derived from *Erica arborea* (rays 5–7/8 cells wide) (figure 3, photos 4–5), which was confirmed by the pollen analysis (see below). Some *Calluna vulgaris* (uniseriate rays, small vessels in a transverse section) could have been present, although scalariform perforations of 2–3 bars high were not observed. Currently, the NW Iberian Peninsula harbours a large diversity of heather species which often occur as the shrub stratum in light oak forests. Heather communities may develop on sunny slopes in combination with *Genista tridentata* to create a formation that adapts well to soil degradation and fire recurrence (Rodríguez Guitián *et al.*, 1996). In NW Iberia, charcoal derived from heather has been frequently observed in archaeological layers and fireplaces (Figueiral, 1993; Carrión, 2005), which is probably related to the flammability and excellent qualities for fire kindling of heather wood.

Two groups of genera from the Fabaceae family (23±21%), F. type *Genista* and F. type *Ulex* (Figure 3, photos 6–7) were identified from the anatomical key characters proposed by Marguerie and Hunot (1992). Fabaceae of the *Genista* type have relatively few multiseriate rays and the cells are narrow in the transversal and tangential sections. On the radial section, ray cells of the *Ulex* type are relatively large and exclusively composed of square and upright cells. According to these criteria, Fabaceae type *Genista* was predominant. Currently, the most frequent Fabaceae genera in the NW Iberian Peninsula are *Genista* (*G. florida*, *G. cinerea*), *Ulex (U. parviflorus)* and *Cytisus* (*C. striatus*, *C. scoparius*, *C. multiflorus*) (Costa *et al*., 1997). The majority of these legumes are heliophytic and pyrophytic species that form part of substitution communities on degraded soils.

Oak species account for 17±20% of the charcoal from PRD-2. Deciduous *Quercus* can be distinguished from evergreen species when the growth-ring boundary is observed because deciduous oaks present conspicuously larger vessels in earlywood (Greguss, 1959), corresponding to the growth of new foliage in spring (Figure 3, photo 11–12). The criteria for oak species determination based on the presence of rows of large vessels in earlywood (Heinz, 1990) are not suitable for small-sized charcoal fragments. In the NW Iberian Peninsula, pedunculate oak (*Quercus robur*) is currently the most abundant.

Arbutus unedo (5±10%; Figure 3, photo 1) has its ecological optimum in the Mediterranean region and is less widespread in Atlantic areas. Formations with strawberry trees are common in open oak communities. After a fire, this species sprouts easily with several new shoots, rendering it an effective competitor (Romo Díez, 1997; Costa *et al.*, 1997).

Other taxa identified were *Betula*, *Clematis*, Pomoideae and *Prunus*. One taxon was identified as common bracken (cf. *Pteridium aquilinum*) (Figure 3, photo 10) according to some characteristic anatomical patterns such as vessels packed in tangential to oblique groups on the transverse section (Schweingruber *et al.*, 2006: 72). The spores of this species were found on the pollen slides from PRD-2, and Figueiral (1996) also identified its charcoal in NW Portugal. However, vitrification of the majority of fragments inhibited unequivocal identification. There was also a high percentage (12.5%) of indeterminable charcoal, sometimes because of the small size of the fragments, but more often because of anatomical alterations that complicate the botanical identification.

Figure 5 shows the depth profile of the four dominant charcoal taxa (*Erica*, Fabaceae, *Quercus* and *Arbutus*), macroscopic charcoal content (> 2 mm) and the proportion of wood with strongly curved rings. The PRD-2 sequence begins *c*. 6100–6300 cal. BP

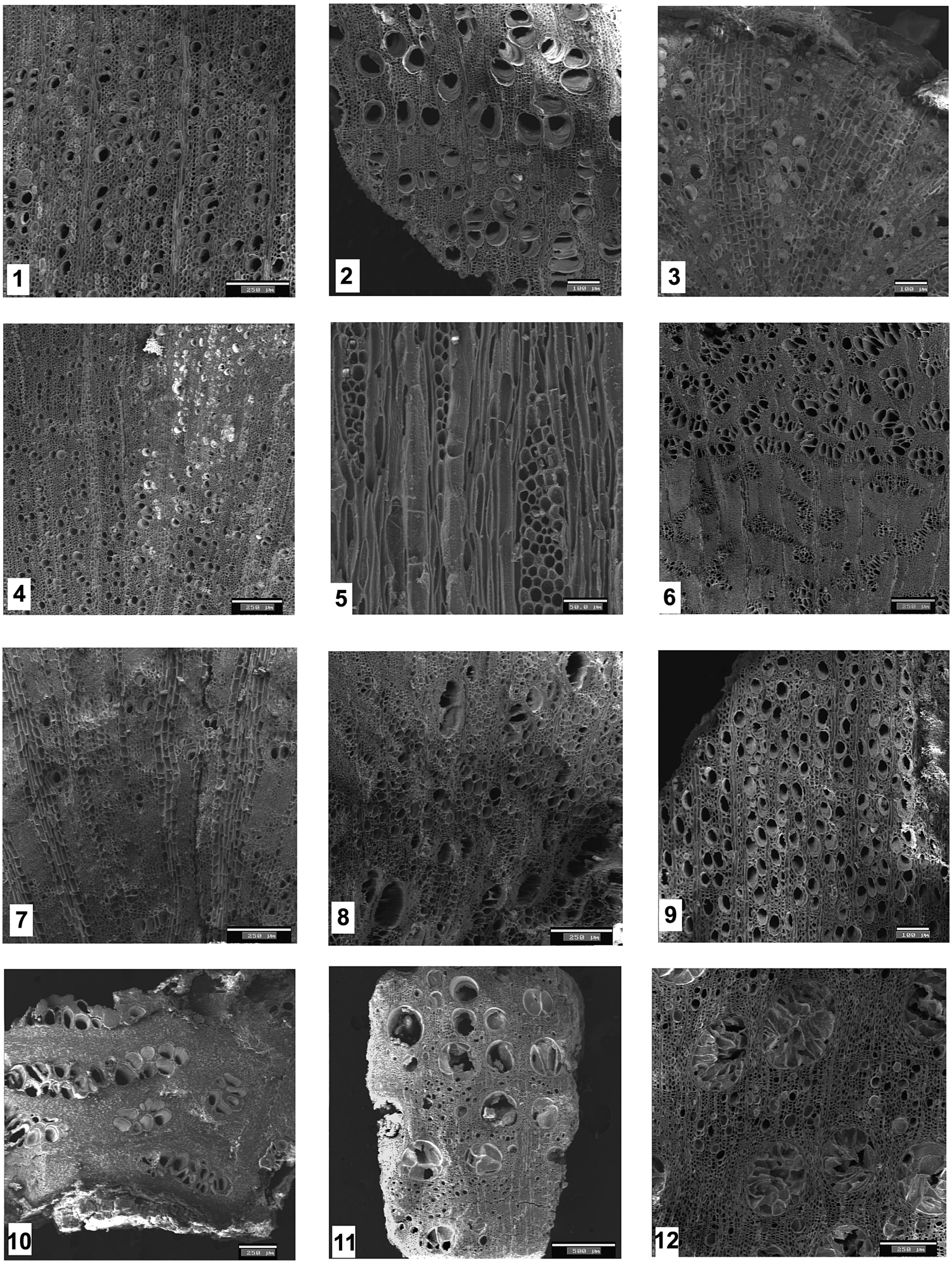

Figure 3 SEM images of some taxa identified in PRD-2. (1) *Arbutus unedo*, transversal section; (2) *Betula* sp., transversal section; (3) *Clematis* sp., transversal section; (4) *Erica* sp., transversal section; (5) *Erica* sp., tangential section; (6) Fabaceae tp. *Genista*, transversal section; (7) Fabaceae tp. *Ulex*, transversal section; (8) Fabaceae, transversal section with radial cracks; (9) Pomoidea, transversal section; (10) cf. *Pteridium aquilinum*, vitrified transversal section; (11) deciduous *Quercus*, transversal section; (12) deciduous *Quercus*, transversal section, detail of tyloses

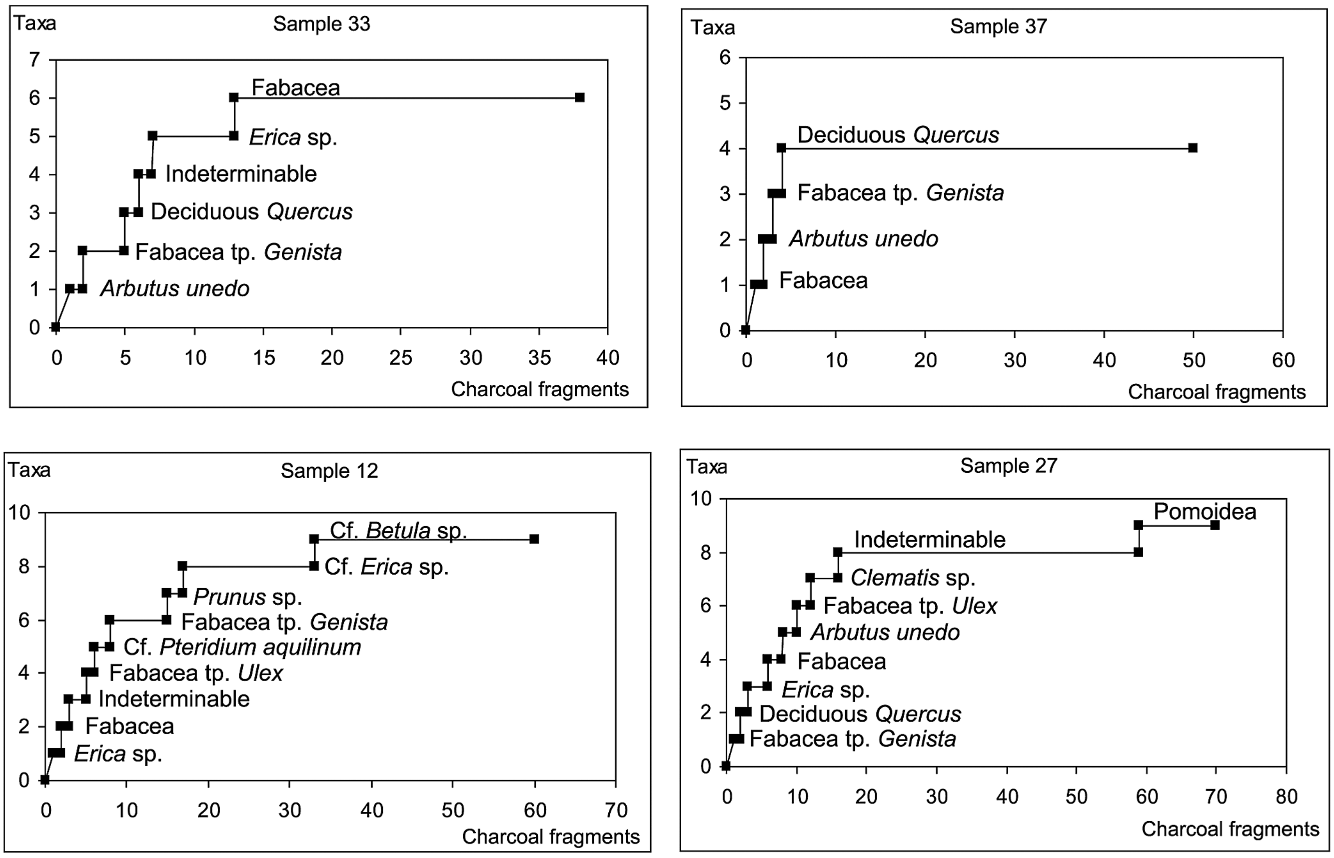

Figure 4 Saturation curves of four samples from PRD-2, as examples of poor charcoal-content levels (37, 33) and samples with 'high' taxonomical diversity (12, 27). In the former samples, no appearance of new taxa is expected; in samples 12 and 27, only some indeterminable and 'cf' taxa (with the exception of Pomoidea in sample 27) impede the complete stabilization of the curves. This method determines the number of charcoal fragments to be identified in order to obtain the optimal representation of the taxa (Chabal, 1997). In most samples of PRD-2 profile, the curves showing the appearance of new taxa are completely stabilized

when most charcoal derived from Fabaceae and *Quercus*. Between 5995–6155 and *c*. 4070 cal. BP, the contribution of *Quercus* decreased from ~65% to ~35%, with a corresponding increase in *Arbutus unedo*. Stones were found in this soil layer (Figure 2). A hiatus in soil stratigraphy of between 185 and 190 cm in depth (Costa Casais *et al.*, 2009) might conceal an even steadier decline in *Quercus* contribution. Thereafter, a second decline in *Quercus* (from ~35% to ~10%) occurred shortly after 4000 cal. BP (160–165 cm) when *Erica* increased from 20% to 47% of the charcoal. The increased proportion of *Erica*-derived charcoal corresponded to an increase in the proportion of wood with strongly curved rings (Figure 5) and charcoal with radial cracks (Figure 3, photo 8), suggesting that relatively mature stands consisting of mainly *Arbutus* and *Quercus* were partially replaced by rapidly rejuvenating heather formations. Ericoid shrubs remained dominant until *c*. 3500 cal. BP, ie, 135–140 cm. The taxonomical composition of the charcoal revealed a strong variation between 140 and 110 cm in depth (*c*. 3500–2800 cal. BP), suggesting rapid vegetation changes that cannot be explained at the current sample resolution. Between *c*. 2800 and 1700 cal. BP (110–85 cm), charcoal from Fabaceae was dominant while *Quercus* gradually disappeared as a result of the formation of heliophyte shrubland. Afterwards at *c*. 1700 cal. BP, a major shift in the charcoal source from Fabaceae to Ericaceae occurred, which coincided not only with a strong increase in macroscopic charcoal content (up to almost 10 g/kg soil), but also with an increase in the percentage of wood with strongly curved rings (Figure 5). The peak in charcoal content also coincided with the highest percentage of charcoal exhibiting radial cracks and vitrification. These results can be interpreted as an accelerated rejuvenation of vegetation as a result of fire regime intensification, which created nearly monospecific heather stands (its proportion in some samples exceeded 95%). After the charcoal peak, however, the soil macroscopic charcoal content declined progressively and the proportion of charcoal with strongly curved rings (and radial cracks) also decreased, suggesting stabilisation of the heather formation that was probably subjected to a less intense fire regime. The settlement of this relatively stable and mature scrub vegetation might have been promoted by soil erosion and a gradual soil impoverishment (eg, acidification and fire-induced nutrient loss), so the forest could not develop properly (Giovannini *et al.*, 1990; Martínez-Cortizas *et al.*, 2000; Kaal *et al.*, 2008c). Indeed, the latest expansion of *Erica* coincided with a peak in coarse (> 2 mm) inorganic soil material which indicates strong erosion.

Some information on fire dynamics can be inferred from these results. The expansion episodes of *Erica* coincide with a clear decline in deciduous *Quercus* charcoal, suggesting that oak is sensitive to fire recurrence (Pausas, 1999). Trabaud (1996) showed that fires in oak woodland reduced total vegetation biomass and taxonomical diversity, and stimulated the expansion of pyrophytic species. In that study, oak regenerated to some extent in the 5–6 years after the fire, unless the site had been burned repeatedly to produce a heather-dominated shrubland. Analogously, the stepwise decline in oak charcoal in the present study was probably associated with rapidly reiterating fire events (supported by the omnipresence of charcoal in the sequence), which partially explains the taxonomic poverty in the charcoal record (Lloret *et al.*, 2005; Pausas, 2006). It is difficult to elucidate the total number of fire episodes recorded in the soil or the interval between them because erosive

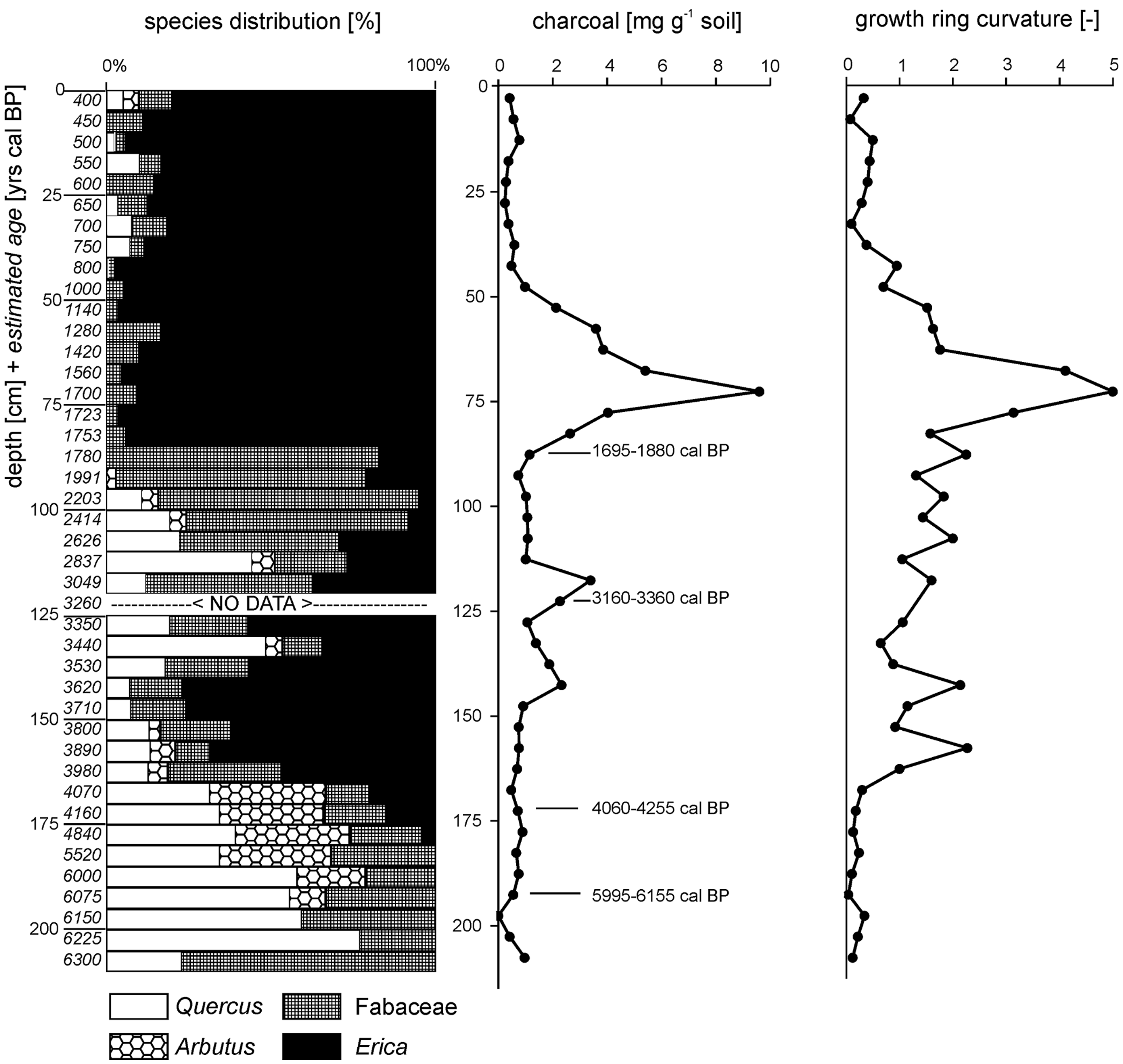

Figure 5 Composition of charcoal assemblages from PRD-2 (simplified), charcoal content and growth-ring curvature (proportion of wood with strongly curved rings) (estimated ages are interpolated from C^{14} dates)

events created the hiatuses in soil stratigraphy and the sampling resolution is insufficient for such purposes. In any case, fires seem to have occurred at short enough intervals to reduce oak regeneration since at least *c*. 2500 cal. BP onwards, which culminated in the definitive settlement of Ericaceae-Fabaceae shrub communities.

Pollen and non-pollen palynomorphs

The pollen record (Figure 6) was dominated by herbaceous plants (20–80%, mainly Poaceae). The dominant tree species was deciduous *Quercus*, while *Alnus* and *Betula* were also observed throughout the profile. A significant proportion of the pollen originated from shrub formations, mainly from *Erica arborea,* but also from *Calluna vulgaris*, *Ulex* type and *Cistus* type. Sedges (Cyperaceae) and ferns (*Pteridium aquilinum*) were also abundant.

The bottom of the sequence, *c*. 6100–6300 cal. BP, showed a high proportion of herbaceous pollen (Figure 6). The woody species were mainly deciduous *Quercus*, *Alnus* sp., *Betula* sp., *Erica arborea*, *Calluna vulgaris* and *Ulex* type. Such pollen assemblages are typical of a light oak-dominated forest, with shrub species and common bracken at open sites combined with dense herbaceous undergrowth. These grasses were mainly Poaceae (35–40%), but species that may be associated with animal husbandry were also present, such as *Plantago lanceolata* and *Urtica dioica* types (Behre, 1981; López Sáez *et al.*, 2003). Between 5995–6155 cal. BP and 4060–4255 BP, the contribution of tree-derived pollen declined abruptly (perhaps associated with the sedimentation hiatus and the stone layer), whereas that of herbaceous pollen increased, suggesting further forest degradation. The simultaneous appearance of coprophilous (dung-living) ascospores of the genus *Sordaria* suggests the presence of local animal husbandry (López Sáez and López Merino, 2007). The NPPs *Glomus* cf. *fasciculatum* and *Pseudoschizaea circula* found in these samples are indicative of soil erosion during this period (López Sáez *et al.*, 1998; van Geel, 2001). The samples at a depth of between 100 and 165 cm (*c*. 4000–2500 cal. BP) are characterised by a decrease in herbaceous pollen and an increase in tree pollen (especially oak),

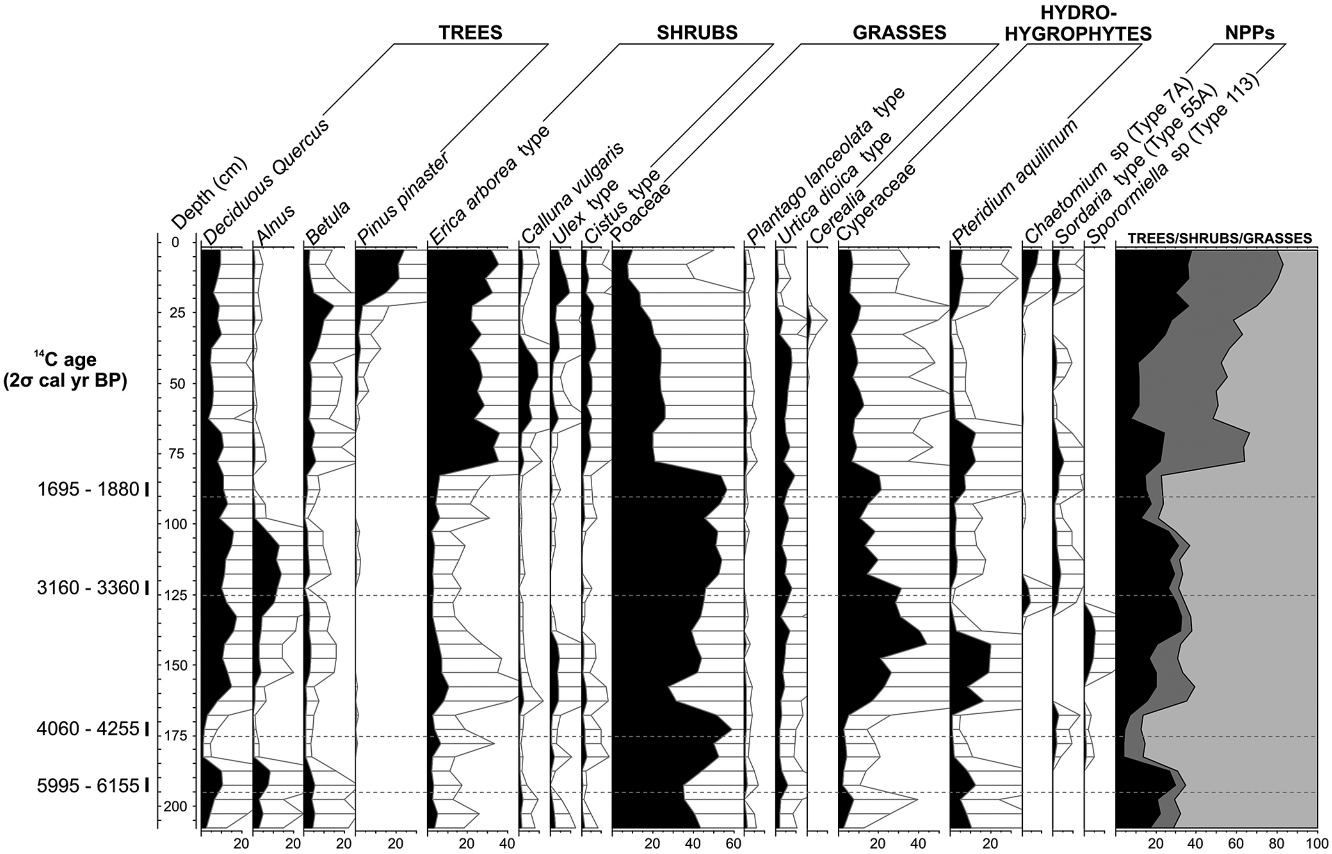

Figure 6 Pollen diagram from PRD-2, including non-pollen palynomorphs (NPPs) percentages (exaggeration is 5%)

Cyperaceae and shrub species (*Erica arborea* type 6–10% and *Ulex* type 5%). The presence of both the coprophilous NPP *Sporormiella* and anthropogenic elements, such as *Plantago lanceolata* and *Urtica dioica* types, are also indicative of human activities in this part of the sequence (López Sáez and López Merino, 2007). In addition, the NPP *Chaetomium* sp. was found, which is thought to thrive on substrates consisting of fire residues (López Sáez *et al.*, 1998, 2000). The high percentage of hygrophilous sedges (Cyperaceae; 20–45%) might indicate more humid conditions in this period. In the second part of this interval, a relative increase in *Alnus* pollen was observed. In the superficial layers of the soil, from a depth of 85 cm towards the surface (*c*. 1700 cal. BP to the present), *Erica arborea* type was the dominant pollen source. The increase of Ericaceae dominated shrub communities (*Erica arborea* and *Calluna vulgaris*) coincided with a decrease in tree and herbaceous pollen and with an increase in the proportion of pollen from ferns (mainly *Pteridium aquilinum*) and *Cistus* type, which is also an evidence of recurrent burning. This period is characterised by forest degradation into shrubland communities ('*matorral*'). *Sordaria* decreased, possibly indicating a reduced pressure from animal grazing, although *Plantago lanceolata* and *Urtica dioica* types were observed. Moreover, pollen from *Castanea* (not shown) and Cerealia were found in surface layers. The percentage of cereal pollen was low (< 3%) and should be considered evidence of agriculture in the proximity of the study site, but not necessarily at the site itself (López Sáez and López Merino, 2005). Pollen from *Pinus pinaster* was abundant in the top 20 cm of the profile.

Charcoal and pollen as proxies of past vegetation

The combined charcoal and pollen records reveal some interesting coincidences. First, both records indicate a first decrease in *Quercus* contribution between *c*. 6000 and *c*. 4000 cal. BP, although the pollen record lacks a corresponding increase in *Arbutus unedo*. Second, the percentages of *Erica* sp. in the pollen and charcoal records were linearly correlated (r^2=0.60; P<0.001; n=41), with both approaches showing a major expansion of ericoid shrubland shortly after *c*. 4000 and *c*. 1700 cal. BP, the latter of which produced a stable and mature formation. Thirdly, some peaks in charcoal concentration (Figure 5) are inversely related to the abundance of tree taxa in charcoal and pollen, which is consistent with other fire–vegetation interaction studies (eg, Colombaroli *et al*., 2008) and modern ecological studies showing a simultaneous trend of woodland cover decline, expansion of shrublands and simplification of the forest structure (Lloret *et al*., 2005; Pausas, 2006). This may be easily explained by the fact that fire promotes the expansion of shrub resprouters (in this case, *Erica*).

But there were also major differences seen between the charcoal and pollen records, such as the relatively small taxonomical diversity of the charcoal. Obviously, non-woody grasses and sedges did not produce macroscopic wood-charcoal, but also many woody species such as *Alnus*, *Betula* and *Pinus pinaster* were not found in the charcoal assemblage, for which an explanation is required. The pollen record provided relatively smooth depth profiles for *Quercus*: the charcoal record suggests that oak diminished in clearly defined phases (*c*. 5500, *c*. 4000 and *c*. 1700 cal. BP), and that Ericaceae-Fabaceae shrubland dominated the site from *c*. 2800 cal. BP onwards. In contrast, the pollen record suggests that tree cover remained significant during the last 2500 years and that the period of oak charcoal decline of *c*. 4000 cal. BP was not observed in the pollen record at all. This discrepancy may be related to the different mobility patterns of pollen and macroscopic charcoal. Most authors agree that unlike microscopic charcoal, large particles (> 125–500 μm in diameter) are not transported over long distances because they settle within or close to

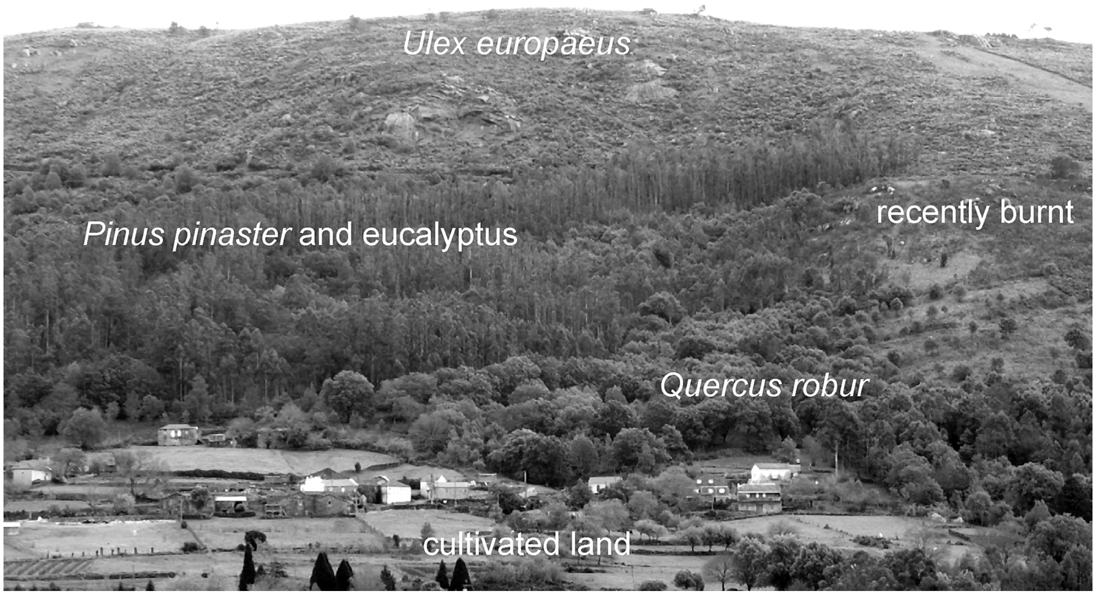

Figure 7 Typical vegetation sequence on a slope near Cerdedo (Pontevedra, Galicia, NW Spain): agriculture and animal husbandry in the valley; oak and eucalypt/pine on the midslope and *Ulex europaeus* on the upper part of the hill

the burned area, which is in agreement with the often-observed rapid decrease in charcoal influx with increasing distance from the fire edge (Clark *et al.*, 1998; Blackford, 2000; Gardner and Whitlock, 2001; Lynch *et al*., 2004; Colombaroli *et al*., 2008). This, however, does not imply that the macroscopic charcoal in Campo Lameiro is immobile because the erosive events in areas subjected to colluviation can also transport heavier and denser materials such as gravel and stones. Nonetheless, we consider that the macroscopic charcoal from PRD-2 must have been produced in the vicinity of the site, at a few hundred metres away on the summit of the hill at the most because these particles cannot be transported uphill (the convectional uplift of macroscopic charcoal during fire is less relevant and less susceptible to wind transport). In addition, the profusion of large charcoal fragments (> 5 mm) may be considered indicative of the very local nature of the charcoal record. On the contrary, however, pollen is transported over long distances so that the pollen record represents the vegetation on a more regional scale. Consequently, the pollen-producing vegetation, that is located further from the study site, is represented by the pollen record but not by the charcoal one. This is especially important for the present case study in a small area on top of hill that undergoes forest regression uphill because of fires: charcoal must be very local while the pollen rain from the lower areas can be easily transported from the nearby valleys and footslopes covered with relatively intact forest vegetation. Uphill pollen transport partially explains the higher taxonomical richness for pollen than for charcoal.

Traditionally, the highland areas of Galicia ('el monte') were subjected to slash-and-burn practices and used as pasture, whereas land use in the relatively fertile soils in the valleys did not involve fire (Criado Boado, 1993). Furthermore, the higher moisture content of the soils on the lowlands may have favoured forest communities and reduced fire sensitivity. It may therefore be assumed that human-induced burning and the consequent degradation of oak forest started in the highlands (the study area) and that the oak pollen found in the soil studied originated largely from areas situated downslope. Pollen input from the surroundings of the site may thus explain why the long-term decline in *Quercus* charcoal was not as evident in the pollen record. Similarly, *Alnus glutinosa* in the NW Iberian Peninsula today is concentrated in the humid river valleys (Rodríguez-Rajo *et al*., 2004). A typical vegetation sequence (Bouhier, 1979; Criado Boado, 1993; Ballesteros, 2003) is still evident at Cerdedo, located ~12 km east of Campo Lameiro (Figure 7): cultivated land and riverside vegetation (eg, *Alnus*) in the valley, oak formations on the lower part of the hill and shrub communities on the upper part (simplified description), in this case with *Pinus* and *Eucalyptu*s plantations in between. In short, *Quercus* and *Alnus* pollen from the valleys could have been transported into upland areas such as the site where PRD-2 is located, producing discrepancies between pollen and charcoal records, the latter being a proxy of more local vegetation.

On the other hand, some species were abundant in the charcoal record but sparse in the pollen sequence (such as Fabaceae and *Arbutus unedo*). This discrepancy may have been the outcome of selective degradation or removal of pollen types (Havinga, 1984). With regard to *Arbutus unedo*, the entomophilous pollination of this species might explain the scarcity of its pollen in sediments. However, the fact that charcoal was primarily formed during periods when pyrophytic species were abundant (such as Fabaceae and Ericaceae) probably added to their over-representation in terms of vegetation composition. Within the average time span represented by the studied samples (*c.* 150 yr), short periods of forest recovery produced pollen, but they are not reflected in the charcoal record. A higher sampling resolution would be required to decide this issue.

Holocene landscape evolution

c. 6300–5500 cal. BP

Soil started accumulating at *c*. 6300 cal. BP, which marked the onset of widespread colluviation in NW Iberia (Fábregas Valcarce *et al*., 2003; Martínez Cortizas *et al.*, 2008, and references therein). During this period, enhanced erosion was often attributed to increased cattle pressure and the corresponding Neolithic system of slash-and-burn agriculture (Martínez Cortizas *et al*., 2008) which led to the decline of the well developed oak formations that dominated coastal forests during the Hypsithermal period (*c*. 8500–6000 cal. BP) (Gómez-Orellana *et al.*, 1998;

Santos *et al.*, 2000; Muñoz Sobrino, 2001; Gómez-Orellana, 2002; Carrión, 2005). An additional purpose of woodland clearance, agriculture, is evidenced by the first appearance of cereal-type pollen and synanthropic species, for example dating back to 6500–6050 cal. BP in the peat record of Tremoal da Pena Veira (Ramil-Rego and Aira Rodríguez, 1993) and to 6450–6240 cal. BP in Chan do Lamoso (Ramil-Rego *et al.*, 1994). In the present work, the charcoal from this period was dominated by *Quercus* and Fabaceae, while pollen reflected the presence of the *Quercus-Alnus-Betula* assemblage with significant herbaceous undergrowth, confirming earlier palynological (Ramil-Rego, 1992; Allen *et al.*, 1996; Santos *et al.*, 2000; Muñoz Sobrino *et al.*, 2005), anthracological (Carrión, 2005) and other macro-remains (García-Amorena *et al.*, 2008) studies from NW Iberia. A partially deforested landscape and the presence of pyrophytic shrubs are highlighted by the combined charcoal and pollen results.

c. *5500–4000 cal. BP*

The soil sequence contains a hiatus in the sedimentation record from possibly between *c*. 6000 and *c*. 5500 cal. BP (Costa Casais *et al*., 2009). Therefore, the age estimations in this period are particularly tentative. Around 5500 cal. BP, the percentage of tree pollen decreased in relation to herbaceous one. The presence of *Plantago lanceolata* and *Urtica dioica* types in the pollen record and the peak of NPP *Sordaria* both suggest the use of fire to generate pasture for animal grazing (Martínez-Cortizas *et al*., 2008). On the other hand, this phase corresponds to relatively cold and humid conditions associated with the Neoglaciation period (Magny *et al.*, 2006) which, in combination with frequent anthropogenic burning, may well explain this period of significant Holocene environmental change in NW Iberia (Fábregas *et al.*, 2003). The onset of progressive soil acidification in NW Iberia during this period (Martínez Cortizas *et al*., 2008) may have resulted from a combination of nutrient depletion, forest retreat and a worsening of the climate.

c. *4000–3500 cal. BP*

Shortly after *c*. 4255–4060 cal. BP, the contribution of *Erica* increased according to the charcoal and pollen records. However, while the charcoal record suggests a decline in *Quercus* (probably as a result of local scale deforestation on the top of the studied hill), the contribution of *Quercus* pollen increased, indicating the recovery of this species probably in the downhill area. The local rejuvenation of vegetation is supported by the increase in charcoal fragments with a strong growth ring curvature, suggesting rapidly reiterating fires which favoured the expansion of heather shrubland. It is worth noting that the sedimentation rate in PRD-2 seemed to increase significantly in this period (30 cm in ~ 500 yr as opposed to 40 cm in the previous ~ 2300 yr), which may be explained by an intensification of the local fire regime (Martínez Cortizas *et al*., 2009). According to Muñoz Sobrino *et al*. (2001), this is the main period of oak forest regression resulting from human impact and is associated with the consolidation of the agropastoral system in NW Iberia (Carrión, 2005, and references therein). The presence of *Urtica dioica* and a peak in NPP *Sporormiella* (López Sáez *et al*., 2009) suggest that stockbreeding was the objective of clearance. However, this interpretation depends strongly on the assumption that the increase in oak pollen reflects forest recovery in the surrounding areas of the study site rather than at the site itself.

c. *3500–2700 cal. BP*

The pollen record reflects a further expansion of forest by the increase in *Alnus* at the expense of heather and gorse shrubland, and also by the climate amelioration coinciding with the end of the Neoglaciation period (Johnsen *et al*., 1992; Ramil-Rego, 1993; Martínez Cortizas *et al*., 1999; Mighall *et al*., 2006). Two peaks in *Quercus* charcoal might suggest forest expansion during intervals before and after *c*. 3160–3360 cal. BP. This would imply a reduction in ecological pressure exerted by fire, which is in agreement with the decrease noted in *Erica* charcoal. The abundance of *Urtica dioica* and the NPP *Sordaria* suggests that the human activity was intense in the area also during this period.

c. *2700–1700 cal. BP*

The charcoal assemblages obtained from the samples, which were estimated to date to *c*. 3200 and *c*. 1700 years old (^{14}C measurements), were dominated by Fabaceae. The pollen sequence displayed a slight increase of *Ulex* sp., although it was lower than the increase in Fabaceae charcoal. *Alnus* decreased from >10% to less than 1%, while oak pollen also presented a slight reduction. The proportion of herbaceous pollen increased significantly. Combined evidence suggests that the regional forest recovery in the previous phases had come to an end and that a renewed intensification of the burning regime gave way to the expansion of shrubland dominated by legumes.

c. *1700–400 cal. BP*

The latest and most striking event was the rapid colonisation of the area by *Erica* sp. shortly after 1695–1870 cal. BP, which was detected somewhat later in pollen than in charcoal (75–80 cm for pollen, 80–85 cm for charcoal). This delay had also been detected in other studies that compare charcoal and pollen sequences (Carrión, 2005; Colombaroli *et al*., 2008). The coincidence of high percentages of *Erica arborea* and *Cistus* type pollens (Figure 6), both of which are well-known post-fire colonisers (Pérula *et al.*, 2003), reaffirms that the progression of degraded heathland at the expense of deciduous *Quercus* was favoured by fire. In PRD-2, the pollen record shows that the expansion of *Erica* sp. coincided with a relative decrease in herbaceous pollen, thus suggesting that the heather formation was dense enough to inhibit the development of a significant herbaceous understorey. A stable, well developed ericoid community was confirmed by the progressive decrease in wood with strongly curved rings after the initial expansion of *Erica*. Ericaceae-Fabaceae formations are sometimes considered to be the best to adapt to the gradual soil impoverishment induced by fire, and a 'pseudo-climax' series in NW Iberia (Rodríguez Guitián *et al.*, 1996), as documented in other charcoal analyses carried out in Galicia (NW Spain) (Carrión, 2005) and Portugal (Figueiral, 1996).

The first appearance of cereal-type pollen in PRD-2, after *c*. 1700 cal. BP occurred quite late in comparison with the first cereal pollen found in Castro de Penalba (2600 cal. BC) (Aira Rodríguez *et al.*, 1990), located a few kilometres from the study site. This period also showed an increased abundance of *Plantago* type and NPPs, indicating an intensified practice of agriculture and/or animal husbandry. In a peat record from Galicia, Martínez Cortizas *et al.* (2005) found two intense phases of forest decline corresponding to the Roman (*c*. 2000–1600 BP) and Germanic periods (*c.* 1500–1400 BP), which may match the age of the charcoal peak *c*. 1700 cal. BP. In that study, only the Germanic phase related to heather expansion, which might suggest that the charcoal peak in PRD-2 corresponds to the beginning of the Germanic period in NW Iberia.

In the youngest part of the sequence, pollen from *Pinus pinaster* was found, which is completely absent in the charcoal record. The pollen from this species may have been transported into the study site from longer distances since it is known for its exceptional aeolian mobility (Tormo *et al.*, 1996). *Pinus pinaster* is currently concentrated on the NE part of the hill, more than 100 m away from the studied profile. Although this species is only present in recent chronologies, it has also been identified in pollen sequences from *c*. 8500 cal. BP onwards, such as Mougás, Caamaño, Aguçadoura or Cortegaça for the coastal areas (Gómez-Orellana, 2002), and Laguna de las Sanguijuelas for the eastern Galician mountains (Muñoz Sobrino, 2001). Thus, the appearance of *Pinus pinaster* in recent times may result from spreading after Roman forestation practices, but also from the expansion of the autochthonous pines of the Iberian Peninsula (Figueiral, 1995).

Conclusions

Palaeobotanical studies carried out in Campo Lameiro show that charcoal, pollen and NPPs form a suitable set of proxies to study the relationship that links fire history, vegetation history and human activities.

The pollen record shows that, in the long term, shrub communities expanded to the detriment of grasses and trees. The abundance of charcoal suggests that this development was associated with fire. A comparison of pollen and charcoal records suggests that this process was much more pronounced on a local scale than on a regional one. The recurrence of NPPs is associated with animal husbandry (*Plantago* type, *Urtica* type) which evidences that human disturbance was the main cause of these transformations.

The combined results obtained indicate that the study site is a locally deforested landscape which has been heavily affected by human activities that probably used fire to generate pasture for cattle grazing, which is in line with Bouhier's assertion that the eroded landscape observed today in much of upland Galicia is largely due to the impact of slash-and-burn or similar practices (Bouhier, 1979; Soto *et al.*, 1995).

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Appendix 1

Frequencies of the taxa identified in charcoal from the PRD-2 profile

Sample/ Taxa	*Arbutus unedo*	*Betula* sp.	*Clematis* sp.	*Erica* sp.	cf. *Erica* sp.	Ericaceae	Fabaceae tp. *Genista*	Fabaceae tp. *Ulex*	Fabaceae	Pomoideae	*Prunus* sp.	cf. *Pteridium aquilinum*	deciduous *Quercus*	*Quercus* sp.	Indeterminable	Species minimal N.	Total
1	1			12	2	2	2						1		2	3	22
2				16			1	1							1	3	19
3				26	3	2	1						1		2	3	35
4				19	2	4	2					1	3		9	3	40
5				20	2	1	3		1						9	2	36
6				26	2		1		2				1		5	3	37
7				19	2	1	3						2		5	3	32
8				36	3		1		1				3		6	3	50
9				42	3	1			1						13	2	60
10			1	48	2	2	1	1	1						4	4	60
11			1	50	1	3			2						13	3	70
12		1		30	3	2	1	3	3		3	3			11	5	60
13				41	4	1	1		4			1			8	2	60
14				41				1	1						7	2	50
15				48	1	1	2		3						5	2	60
16			1	54			2								3	3	60
17				46		1			3						10	2	60
18				7			7	4	22	1		3			6	4	50
19	1			7			8	1	16			4			9	4	46
20	1			1			4	4	7			8	2		3	5	30
21	2			3			7	5	13				7		7	5	44

(Continurd)

Appendix 1 *(Continued)*

Sample/ Taxa	*Arbutus unedo*	*Betula* sp.	*Clematis* sp.	*Erica* sp.	cf. *Erica* sp.	Ericaceae	Fabaceae tp. *Genista*	Fabaceae tp. *Ulex*	Fabaceae	Pomoideae	Prunus sp.	cf. *Pteridium aquilinum*	deciduous *Quercus*	*Quercus* sp.	Indeterminable	Species minimal N.	Total
22				7	3	2	17		3				9		8	3	49
23	3		4	11			8		1				18		5	5	50
24			1	18	1		24		2	1			6		6	5	59
26		1		24			5	1	4				8		7	5	50
27	3		1	17	3		4	2	1	1			28		7	7	67
28				28		1	11		2				9		9	3	60
29				56			7	1	4				5		7	4	80
30				58	2	2	10		4	1			5	1	17	4	100
31	2			32	2		7		5	1			7		13	5	69
32	3			24	1	1	2		2				5		12	4	50
33	2			14	1		10		1				4		6	4	38
34	16			9			6						14		5	4	50
35	17			7		1	8		2				18		7	4	60
36	16	2		2			10					1	17	1	5	5	54
37	16						11		4				16		3	3	50
38	7						6		1				18	1		3	33
39	3						8	1					13	2		4	27
40							17		1				26		3	2	47
41							14						46			2	60
42							24						7			2	31

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