Did prehistoric and Roman mining and metallurgy have a significant impact on vegetation?

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Abstract

To develop our understanding of the relationship between vegetation change and past mining and metallurgy new approaches and further studies are required to ascertain the significance of the environmental impacts of the metallurgical industry. Using new pollen and geochemical data from Cors Fochno (Borth Bog), Wales, we examine whether prehistoric and Roman mining and metallurgy had a significant impact on the development of vegetation and compare the findings with previous studies across Europe on contamination and vegetation change to develop a conceptual model. The evidence suggests that early mining and metallurgy had a minimal impact on vegetation, especially woodlands, with small-scale, non-permanent phases of woodland clearance. The impact was more severe during Roman times, but very few sites show woodland clearance followed by regeneration. Records do suggest that woodlands underwent compositional changes in tandem with increased atmospheric pollution, possibly in part as a result of demands for wood fuel for mining and metallurgy, but otherwise woodlands show a degree of resilience. The results from Cors Fochno suggest that vegetation changes that occurred during periods of mining and metallurgy, as inferred from changepoint analysis, were insignificant compared to later periods, including Roman times.

Keywords: mining, metallurgy, pollen, changepoint analysis, Bronze Age, Roman, woodlands

1. Introduction

The advent of mining and metallurgy in the Chalcolithic-Early Bronze Age represents one of the most significant social, technological and (potentially) environmental transformations in human history. Over the last two decades there has been an upsurge in interest in the environmental impacts of this transformation, primarily focusing on two areas: metal contamination and vegetation change. A number of studies have reconstructed the pollution history of past mining and metallurgy in Europe, particularly of metals considered to be immobile in ombrotrophic peat such as lead (Pb) and copper (Cu) (e.g. Monna et al., 2004; Kylander et al., 2005; Küttner et al., 2014), the Near East (e.g. Pyatt et al, 2000) and North America (e.g. Pompeani et al., 2013) to establish the timing, severity and longevity of metal contamination which now extends back to the Early Bronze Age in Europe (e.g. Mighall et al., 2002a; Garcia-Alix et al., 2013; Pontevedra-Pombal et al., 2013; Martínez Cortizas et al. 2016).

Until recently the impact of mining and metallurgy on vegetation was poorly understood but investigations in regions with a long history of ferrous and non-ferrous mining and metallurgy are beginning to rectify this situation (e.g. Küster and Rehfuess 1997; Breitenlechner et al., 2010; López Merino et al., 2013; Mighall et al., 2010; 2012; Viehweider et al., 2015). These studies include those that are specific to a mine or furnace (e.g. Mighall et al., 1993; 2002a, b; Mighall et al., 2000; Myrstener et al., 2016) and those that are more regional in scope (e.g. Mighall et al., 2009; Silva-Sánchez et al., 2015). As mining and metallurgy does not occur in isolation and other activities, such as agriculture, occurred during periods of industrial activities, numerous studies have benefited by combining records of metals associated with pollution in tandem with pollen records to discriminate between industrial activity and other land use changes, but have also debated the impact mining and/or metallurgy had on vegetation, particularly woodlands: whether they were largely destroyed by mining and metallurgy or not. A series of studies now suggest that in prehistoric times mining/metallurgy did not have an adverse impact on woodlands (e.g. Marshall et al., 1999; Mighall et al., 2004; Jouffroy-Bapicot et al., 2007; Breitenlechner et al., 2010, 2013; Bindler et al., 2011; Viehweider et al., 2015) with Mighall and Chambers (1997) suggesting that any impact was influenced by some form of management, selectivity, the scale and duration of ironworking as well as other land use strategies. A further methodological advance is the use of changepoint analysis on such data which now allows us to assess the significance of environmental changes more objectively (Gallagher et al., 2011) and has been applied successfully to datasets derived from bogs (e.g. Kylander et al., 2013; Hansson et al., 2013; Martínez Cortizas et al., 2016).

In order to establish the impact of mining and/or metallurgy on woodlands more studies are needed. Therefore we present new pollen and geochemical data from Cors Fochno (Borth Bog) to exemplify whether such activities had a significant impact on the vegetation history at the site and compare the findings with previous studies across Europe to identify patterns in the data that could lead to a conceptual model of such impacts. This will be accomplished by discriminating between environmental changes caused by mining and metallurgy from other types of land use by performing principal component analysis on the geochemical data, and to identify significant vegetation changes were caused by mining and/or metallurgy using changepoint analysis.

2. Site details and context

Over 250 archaeological sites are recorded on the Dyfed Historic Environment Record in and around the Cors Fochno, ranging in date from Mesolithic find spots to twentieth century military installations (Page et al., 2012). One of the most important archaeological discoveries is the evidence for early mining of metal-bearing deposits including chalcopyrite (copper iron sulphide), galena (lead sulphide) and sphalerite (zinc sulphide) (Timberlake, 1995a, b, 1996a, 2003a). Eight Early Bronze Age mines have been identified in mid- and north Wales, including an area of prehistoric prospection and mining around Cors Fochno

(Figure 1a-c). Bronze Age copper mining is suspected at Llancynfelin, Pwll Roman and Erglodd along the western fringe of the bog (Timberlake, 2006) but some may have been prospecting rather than actual mining (Timberlake, 2009) (Figure 1c). Roman lead smelting also occurred at Llancynfelin, close to the Erglodd Roman fort during the first century AD (Page et al., 2012; Figure 1b). The Blaen yr Esgair Roman road has been radiocarbon-dated to c. AD 80. Mighall et al. (2009) presented a record of metal contamination that suggests lead mining and/or metallurgy surrounding the bog occurring in the Bronze Age, late Iron Age and Roman times.

Cors Fochno (Borth Bog) is an estuarine lowland raised bog located in northern Ceredigion, north of Aberystwyth that forms part of the Dyfed SSSI and National Nature Reserve and a UNESCO Biosphere Reserve. The bog is approximately 200 ha in extent and surrounded by a further 400 ha of degraded bog that has suffered from past peat cutting and drainage (Poucher, 2009). A full description of the bog is provided in Hughes and Schulz (2001). Cors Fochno is underlain by Silurian Aberystwyth grits group with outcrops of Ashgill beds (mudstones and siltstones to the east) (Howells, 2007).

Pollen diagrams have been published from Cors Fochno (Borth Bog) by Godwin and Newton (1938), Godwin (1943) and Moore (1968). All three studies are constrained by the absence of radiometric dating and Godwin only published tree pollen data. More recently, Page et al. (2012) published pollen data for the site but this record focusses solely on the Late Iron Age – Roman period. Other studies have focussed upon mire development (Hughes and Schulz, 2001; Hughes et al. 2007). Given the limitations of the pollen-based studies and the recent discovery of new archaeological sites surrounding the bog (outlined below), a new investigation is timely.

The location of the sampling sites in this study is shown in figure 1c. The coring location is SN63548 91373, elevation 3±5 m OD. A 7 m-deep core was taken from the raised bog to provide a regional record of pollution and vegetation change. The top 4 m of the core are considered in this paper as it covers the period of interest.

3. Methods and materials

A core was collected using a 30-cm long, 9-cm wide Russian corer, wrapped in plastic, sealed and stored in a cold store prior to sub-sampling for geochemical and microfossil analyses.

3.1 Dating methods: Five peat samples were carefully extracted and submitted to the Beta Analytical, Miami or Poznań radiocarbon laboratory for AMS radiocarbon dating (Table 1). Three of the samples comprised bulk sediment, whilst two (BB52-53 cm and 170-171cm) were *Sphagnum* leaves.

^{210}Pb dating was undertaken on 1 cm thick contiguous samples taken from the upper 20 cm of the core to define more precisely the age of the uppermost part of the sequence and to detect any hiatus in modern peat accumulation. Full details of energy and efficiency calibration methods, and of quality control, are given by Foster et al. (2005) and Mighall et al. (2009). ^{214}Pb was measured in order to obtain ^{226}Ra activities that were subtracted from the total ^{210}Pb activity to calculate the unsupported ($^{210}Pb_{un}$) component in the samples.

3.2. Geochemistry: Concentrations of major elements (Si, Al, Fe, Ca, K), trace lithogenic elements (Rb, Sr, Ti, Zr, Y) and trace metals/metalloids (Cu, Cr, Zn, Ni, Pb and As) were obtained by energy dispersive X-ray fluorescence (EMMA-XRF) analysis (Cheburkin and Shotyk, 1996; Weiss and Shotyk 1998). The instruments are hosted at the RIAIDT (Infrastructure Network for the Support of Research and Technological Development) facility of the University of Santiago de Compostela (Spain). Standard reference materials were used for the calibration of the instruments. Quantification limits were 0.001 % for Ti, 0.01% for Si, Al and Fe, 0.5 $\mu g\ g^{-1}$ for Pb, 10 $\mu g\ g^{-1}$ for Cr and 1 $\mu g\ g^{-1}$ for the other elements. Replicate measurements were performed on one of every five samples in order to account for reproducibility; all replicates agreed within 5%. Loss on ignition percentages (LOI) were also determined following Schulte and Hopkins (1996).

3.3. Microfossils: Sub-samples of 1 cm thickness were prepared for pollen and non-pollen palynomorph (NPPs) analyses following Barber (1976). A minimum sum of at least 300 total land pollen (TLP) was achieved for all sub-samples in order to produce a statistically significant result (Birks & Birks, 1980). Data are expressed as a percentage of the TLP, with spores and aquatic taxa excluded from the TLP sum. NPPs were also counted (cf. van Geel et al. 1982/1983, 2003) and they are expressed as a percentage of TLP plus total NPPs. Rare types are indicated by a cross (+), where one cross is equal to one pollen grain or NPP. Pollen samples were spiked with *Lycopodium clavatum* tablets (Stockmarr, 1971). Microscopic charcoal was counted during routine pollen analysis. Pollen identification, including cereal-type pollen, was aided by reference keys in Fægri et al. (1989), Moore et al. (1991) and Reille (1999), and supported by a modern type-slide reference collection. As the separation of *Myrica gale* from *Corylus avellana*-type can be difficult these pollen grain types are classified as *Corylus avellana*-type (Edwards 1981). Plant nomenclature follows Stace (2001). Non-pollen palynomorphs were identified using van Geel (1978), van Geel et al. (2005; 2006).

3.4 Statistics: The use of multivariate statistical approaches helps to summarize common patterns of variation and to gain insights into the underlying environmental factors. Therefore, principal component analyses (PCA) was applied to the geochemical data using SPSS 20, in correlation mode and by applying a varimax rotation (Silva-Sánchez et al., 2014). Prior to analysis the dataset was standardized using z-scores, which avoids scaling effects and gives average-centred distributions (Eriksson, 1999). Changepoint (CP) modelling was applied to the pollen data (total trees, shrubs, herbs) to detect significant changes in the pollen record statistically. This approach is based on Bayesian transdimensional Markov chain Monte Carlo (for more details see Gallagher et al., 2011).

4. Results

4.1 Stratigraphy: The core was taken from the central area of the raised bog with *Myrica gale*, *Calluna vulgaris*, *Eriophorum*, *Molinia* and *Sphagna* characterising the surface vegetation. The core was 7 m in length and consists primarily of *Sphagnum* peat of varying stages of decomposition in the top 5.6 m, overlying an herbaceous (*Phragmites*) peat sitting on top of estuarine clay at 6.94 m. A full description of the stratigraphy is provided in Mighall et al. (2009). At the time of coring, the water table was close to surface at approximately 10-15 cm depth.

4.2. Dating: All radiocarbon dates quoted in this paper are listed in Table 1. The uncalibrated radiocarbon dates and calibrated ages cited to 2σ age, using Calib 7.1 software (Reimer et al., 2009) in conjunction with Reimer et al. (2013). The *cic* and *crs* $^{210}Pb_{un}$ dating calculations of Appleby and Oldfield (1978) were both used to establish a chronology for the upper 20 cm of the peat section for the core. Full details can be found in Mighall et al. (2009). The analysis suggests that the record of modern peat accumulation, extending back approximately 150 years, has been preserved at this location, although earlier phases of peat cutting cannot be eliminated on the basis of these results. Both the radiocarbon dates and $^{210}Pb_{un}$ dating were used to construct an age-depth model using CLAM (Blaauw, 2010) (Figure 2). All dates are rounded to the nearest half decade and are expressed in calendar years AD/BC unless stated otherwise. 0 BP is equated to AD 1950.

4.3. Loss-on-ignition & geochemistry: LOI values fluctuate between 97-98% from 400 cm to 300 cm. One value at 120 cm dips to below 96% then they regularly exceed 98% thereafter (Figure 3).

Four components, with eigenvalues greater than 1, account for 83% of the total variance of the chemical composition of the peat samples (Cp1 32.4%, Cp2 28.7%, Cp3 12.8% and Cp4 9%) but only three are discussed as Cp4 offers no useful insights. The record of scores of the first three components are shown in Figure 4 and the fractionation of communalities in supplementary figure 1. Most major and trace lithogenic elements (Ti, Zr, Si, Rb, Al, and Y) show large positive loadings in Cp1 (Table 2; Supplementary figure 2), while K shows a moderate loading. Small proportions (11-17%) of the variance of metals like Fe, Pb and Cu, are also allocated to this component. The depth distribution of scores (Figure 4) shows low variation below 150 cm, with small peaks at 349, 297 and 257 cm depth. Above 150 cm values are more variable with larger and more discernible peaks at 149, 121, 69, 49, 41 and 8 cm.

Cp2 is characterised by large (Fe, Pb, Zn, As, Cu) and moderate (Ni) positive loadings of metallic elements (Table 2; Supplementary figure 2). Some lithogenic elements, as Y, K and Si, also have part (10-36%) of their variance in this component. The record of scores (Figure 4) shows almost constant values until 37 cm depth, from which values increase abruptly to the top of the core. It is noticeable that the large peaks in Cp1 scores in the upper 150 cm of the core coincide with decreases in Cp2 scores.

Cp3 is almost exclusively related to the variation of Ca and Sr concentrations. The scores show negative values below 297 cm, a brief increase from 297 to 285 cm, another decrease until 255 cm, to increase suddenly to positive values and remain high until 69 cm. From this depth to the surface, values decrease to negative scores then increase slightly again in the upper 9 cm of the core (Figure 4).

4.4. Microfossils: The pollen and NPP diagrams were constructed using Tilia.graph (Grimm, 2004) and selected taxa are presented in Figure 5a-c. The diagrams have been divided into local pollen assemblage zones (LPAZs) guided by CONISS (Grimm 1987). Full diagrams are provided in supplementary figures 3a-c.

4.5. Changepoint analysis: The changepoint analysis results are shown in Figure 6. Significant changepoints occur at c. 2400 BC, 1950 BC, 1000 BC, 780 BC, 500 BC, 0 AD/BC, AD 200, AD 1200, AD 1375 and in the last 200 years.

5. Interpretation and chronology of the changes

5.1 Geochemistry: Cp1 is characterised by positive loadings of lithogenic elements (Ti, Zr, Si, Rb, Al, Y, K), which may reflect variations in the mineral content of the peat due to changes in atmospheric dust deposition, probably linked to soil erosion (Table 2). The Cp1 record (Figure 4) indicates low dust deposition before the late Iron Age-Roman period, with a few dust events dating to 2440, 1600-1500 and 1000 BC. From the late Iron Age-Roman period, the number and intensity of the dust-deposition events increased, peaking at c. 30 BC, c. AD 280, c. AD 660, c. AD 940, c. AD 1160-1420 and c. AD 1880-1950.

Cp2 is reflecting a relatively recent (historical) increase in the deposition of metals, most possibly as a result of (poly-metallic)-atmospheric pollution. The record of scores (Figure 4) shows almost constant values until c. AD 1500 and a rapid increase thereafter. Minor fluctuations, for example, between 290 and 275 cm, 240 cm and 210 cm do occur and they could represent slight changes in the intensity of dust deposition. This pollution signal was somewhat masked during episodes of intense atmospheric dust deposition (i.e. enhanced soil erosion). Nevertheless, the fact that a few lithogenic elements (Y, K, Si) also load partly on this component points to a contribution by dust deposition, most likely related to mining operations rather than to metallurgically-derived metal emissions.

Cp3 is likely to reflect a mineralogical/source effect. Elements with large loadings in Cp1 occur in higher concentrations in acidic rocks and soils (hosted in silicates as K-feldspars and muscovite), while the elements characterising Cp3 have higher concentrations in calcalkaline and basic rocks (e.g. rich in plagioclase and amphibole) and they are also typical of carbonates. Thus, this component traces changes in the source of part of the atmospheric dust deposited in the mire. While Cp1 elements and related minerals probably derive from the dominant local geology (Silurian mudstones and sandstones), no geological material in the immediate surroundings of the mire seems to contain Ca-rich minerals; but intrusive and extrusive volcanic rocks of Ordovician age, located approximately a few tens of kilometres north and east of Cors Fochno, may contain large amounts of plagioclase and amphibole. Thus, changes in Cp3 scores may reflect regional rather than local dust sources. The Ca-rich dust source seems to have been less active from c. 3500 to 1000 BC, except for a brief phase between c. 1600-1380 BC; from c. 1000 BC to AD 1000, it made a significant contribution to the dusts deposited on Cors Fochno mire, decreased sharply until the mid AD 18th century and resumed its contribution up until the present.

The variance of some of the metals (Fe, Pb and Cu) is related in part to Cp1, indicating that their content in Cors Fochno peat also has a geogenic origin. In contrast, the chronology of scores of the metal signal reflects recent rather than earlier metal pollution. The PCA results suggest that most of the metal pollution (72-70% of the Fe and Pb variance, 68-59% of that of Zn, As and Cu, and 30% of that of Ni) occurred in the last 500 years and may have been related to mining/metallurgy. The extracted components do not reveal the history of pre-industrial metal contamination: this signal is not strong and its history may have been different for each metal. To determine if the record of concentrations contains information on other sources of pollution we extracted the residual variance for Pb, Zn and As (rPb, rZn, rAs) i.e. the variation in metal concentrations not explained by recent poly-metallic pollution or by changes in soil dust influx (Figure 7). This was done by detrending the record of the metal concentrations (in Z scores) from the components in which its variance is allocated (Cp1 and Cp2 outlined above). Relatively elevated values were detected for each element. Eight phases are detected for Pb: > c. 2980 BC, c. 1500-900 BC, c. 630-540 BC, c. 300 BC to c. AD 100, c. AD 330-560, c. AD 1000, c. AD 1420-1700, and from c. AD 1800 to show an abrupt decline in recent decades; five phases for Zn: c. 2670-1700 BC, c. 540-350 BC, c. 30 BC, c. AD 280, c. AD 800-1800; and six phases for As: c. 1600-1000 BC, c. 230 BC, c. 30 BC, c. AD 280, c. AD 940, c. AD 1270-1690 and c. AD 1925. These variations seem to reconstruct both pre-industrial and industrial Pb pollution (ancient mining and metallurgy, coal burning, combustion of fossil fuels, etc.) and compare favourably to those presented by Mighall et al. (2009). The record of Cu residual variance did not show significant changes (probably because most of the concentrations are close to the limit of detection), while Fe residual variance is difficult to interpret due to the redox behaviour of this element.

5.2 Pollen & NPPs: LPAZ CF1a (400-347 cm; c. 3300-2400 BC): is characterised by fluctuations in total arboreal pollen (trees and shrubs), mainly variations in the percentages of the dominant tree taxa (*Quercus*, *Betula* and *Alnus*) and *Corylus avellana*-type. These variations might be the result of disturbance although evidence of human activity in the pollen diagram is mute. Poaceae percentages were low and non-arboreal pollen taxa associated with cultural affinities only occurred sporadically and in trace amounts: for example, *Artemisia*-type, *Aster*-type, *Plantago lanceolata*, *Plantago media/major*, *Potentilla*-type, Chenopodiaceae and Ranunculaceae. This implies that any activity was small-scale or of insufficient intensity to be registered in the more central parts of the bog (Figure 5a, b).

LPAZ CF1b (347-325 cm; c. 2400-2030 BC): This represents a period of high arboreal tree and shrub percentages. Total tree pollen initially increased, coincident with a substantial but temporary decrease in *Corylus avellana*-type, at the end of LPAZ CF1a and throughout LPAZ CF1b. Notwithstanding the occasional, short-lived recovery, phases of woodland interference is further indicated by a gradual decline in total tree pollen with *Quercus*, and, to a lesser extent, *Betula* and *Alnus*, but total arboreal pollen values remain high compared with the previous zone.

There was a sustained increase in Poaceae and *Plantago lanceolata* occurs regularly. *Rumex acetosa*-type and Ranunculaceae were recorded and *Aster*-type occurred more sporadically in trace amounts indicative of minor disturbance and/or pasture. *Sordaria*-type (HdV55A/B) was recorded for the first time suggesting low intensity grazing and/or the presence of decayed wood (Figure 5c).

LPAZ CF1c (325- 301 cm; c. 2030 – 1630 BC): Total arboreal percentages are much lower in the sub-LPAZ: the major trees all decline. The decline of *Alnus* and *Betula*, suggests that clearance took place on the wetter fringes of the bog and with *Ulmus* and *Quercus* affected on drier substrates. *Quercus* decreased quite rapidly. *Corylus avellana*-type recovers to approximately its CF1a LPAZ values. Hazel scrubland appears to have replaced mixed woodland but some of the increase in *Corylus avellana*-type might be in response to *Myrica gale* colonising more minerotrophic conditions prevalent on the edge of the bog.

Evidence for agriculture and/or disturbance, as described in the previous sub LPAZ continues. The first occurrence of cereal-type pollen was recorded *c*. 1960 BC and coincided with a small peak in microscopic charcoal and a decline in *Quercus*, *Betula* and *Alnus*, although *Corylus avellana*-type increased in value. Fire could have been used to clear woodland for agriculture but wood was used for mining activity and the microscopic charcoal peaks might represent the burning of branchwood in the mines to break up the ore (commonly referred to as firesetting).

LPAZ CF1d (301-265 cm; c. 1630-1090 BC): Woodland (mainly *Quercus*, *Alnus* and *Betula*) regenerated gradually throughout LPAZ CF1d, as indicated by the increase in total arboreal pollen percentages. In contrast, *Alnus* initially declined along with *Corylus avellana*-type, which suggests that any clearance was concentrated on wetter substrates, perhaps on the fringe of the bog. Bog plants also responded, including a rise in *Calluna* and *Sphagnum*, which also implies that they might be replacing *Myrica*. Notwithstanding any taphonomic effect on the pollen rain, taxa indicative of pasture and/or disturbance were recorded at the start and end of the LPAZ: Poaceae, *Plantago lanceolata*, *Artemisia*-type and *Pteridium* peak, and *Aster*-type, *Rumex acetosa* type and Ranunculaceae were recorded in trace amounts (Brown et al., 2007). Cereal-type pollen was also present (Figures 5a, b).

LPAZ CF1e (265 cm-249 cm; c. 1630-900 BC): A phase of woodland clearance occurs throughout this LPAZ. All the major tree and shrubs are adversely affected. It marks the first significant, permanent decline in woodland during the mid to late Bronze Age. Poaceae, *Plantago lanceolata*, *Potentilla*-type and *Pteridium* initially peaked and trace amounts of *Artemisia*-type, *Rumex acetosa*-type, Chenopodiaceae and Ranunculaceae were recorded.

LPAZ CF2 (249 – 205 cm; c. 900-520 BC): Woodland recovers slightly at the start of the LPAZ. *Quercus*, *Betula* and *Alnus* all increase in value. Evidence for human activity in the non-arboreal record is then mute at this time. In contrast, *Calluna* percentages rose across the LPAZ sub zone boundary and this sudden increase might have masked any human disturbance signal in the pollen record as plants within a couple of metres of the sampling point can dominate the pollen assemblage and therefore proportions of those taxa associated with land use changes in the wider landscape may be poorly represented (Bunting, 2003). As *Calluna* percentages began to decrease by 230 cm, c. 700 BC, human activity was more evident with the occurrence of cereal-type pollen and an increase in *Plantago lanceolata* percentages. The sudden peak in microscopic charcoal was most likely to have been caused by a short-lived fire close to the sampling site.

In the latter stages of the LPAZ, tree cover, reflected by much lower pollen percentages, reached a LPAZ minimum at 214 cm, c. 600 BC. Hazel scrub woodland appears to have been more dominant, as *Corylus avellana*-type percentages started to increase mid-LPAZ. Evidence for human activity remains elusive in the non-arboreal pollen record. Only *Plantago lanceolata* increased but some cultivation is suggested by the isolated occurrence of cereal-type pollen.

LPAZ CF3 (205 – 145 cm, c. 520 BC- AD 20): The period of woodland regeneration across the LPAZ CF2/3 boundary. Total tree percentages remained fairly stable throughout the Iron Age

(LPAZ CF3) but *Corylus avellana*-type percentages decreased substantially. Land was being used for pasture and cultivation: indicators include a slight increase in Poaceae, *Plantago lanceolata* continued to be well represented and a suite of non-arboreal taxa occurred, albeit sporadically and in trace amounts, including Ranunculaceae, Urticaceae, Chenopodiaceae, *Rumex acetosa*-type, *Potentilla*-type, *Aster*-type, *Artemisia*-type and *Anthemis*-type. Low percentages of 'anthropogenic indicator' taxa probably originated from the wider landscape rather than agricultural activity in the near vicinity of the sampling point (Bunting, 2003). Cereal-type pollen was also recorded. *Cercophora*-type, *Sordaria*-type and *Chaetomium* sp. are also suggestive of low intensity grazing and/or the presence of decayed wood (Figure 5c). The spores of the wood rot fungus, *Kretzschmaria deusta* is indicative of possible woodland openings (Innes et al., 2006). Microscopic charcoal values also gradually increased, suggesting that natural or deliberate fires were a regular occurrence, possibly to clear woodland.

LPAZ CF4 (145-129 cm; c. AD 20 - 200): Woodland clearance accelerated across the LPAZ CF3/4 boundary. All the major trees and shrubs were affected until the start of the Roman period, until c. AD 70. Bog plants and NPPs seem to benefit most as a short-lived, sharp increase in *Calluna* was followed by Cyperaceae and HdV-18. Bog surface conditions may have been wetter as HdV-72A is indicative of pools of water and dry indicators such as HdV-10 decline (Figure 5c). This might have been influenced by climate as a stacked record of proxy climate for northern Britain indicates a shift to wetter conditions c. 2050 Cal BP (Charman et al., 2006). Evidence for arable and pastoral agriculture was still subtle. Poaceae peaked just after LPAZ tree percentage minimum. *Plantago lanceolata* and *Rumex acetosa*-type had a low, sustained presence and there were short-lived peaks or traces of *Plantago* *media/major*, *Rumex acetosella*, Lactuceae, *Aster*-type, *Trifolium*-type, *Potentilla*-type and Chenopodiaceae, as well as one cereal-type pollen grain. *Pteridium* also increases in value. (Figure 5b).

LPAZ CF5 (129-43 cm; c. AD 200 - 1380): Woodland regenerated more rapidly from c. AD 210, the start of LPAZ CF5. All the major trees and shrubs increased in representation until the very end of the LPAZ. Poaceae and *Plantago lanceolata* percentages fell to lower values but both taxa were still well represented. Cereal-type pollen was present at the start and towards the end of the zone while pastoral indicators persisted albeit sporadically and in trace amounts (Figure 5b). Sporadic occurrences of *Tripterospora*-type and *Sordaria*-type (HdV55A/B) suggest low intensity grazing and/or the presence of decayed wood (Figure 5c). Woodland cover remained relatively stable as total arboreal pollen percentages fluctuated around 40% TLP into the early medieval period.

LPAZ CF6 (43-9 cm; c. AD 1380 – 1920): A rapid phase of woodland clearance occurred during the medieval and post medieval periods, commencing c. AD 1160 at the end of LPAZ CF5 into CF6. All the major trees and shrubs were affected. Agricultural activities appear to have been an important driver of woodland clearance and soil erosion. Cereal-type pollen is relatively abundant. Poaceae and *Plantago lanceolata* percentages attain their highest values and a suite of taxa with pastoral affinities and the dung fungus *Podospora* type were present (Figure 5b, c).

LPAZ CF7 (9-0 cm; c. AD 1920-2000): The modern period is characterised by woodland regeneration, most notably *Quercus* and *Corylus avellana*-type. *Pinus* pollen percentages rose rapidly, indicative of plantations (Figure 6a). *Helicon pluriseptatum* (HdV30) may derive from the plantations of *Picea* and *Pinus* (Yeloff et al., 2007). The evidence for agricultural activity, described earlier for the medieval period, is still present but not as intense. Cereal-type pollen is recorded for the last time in trace amounts at the LPAZ boundary. The rise in charcoal is likely to have been caused by local bog or woodland fires and domestic activities.

6. Discussion

6.1: Vegetation change associated with human activity: The first significant change of vegetation in the Cors Fochno pollen record occurs during the later Neolithic period (LPAZ CF1a/b zone boundary ~2400 BC; 347 cm). Changepoint analysis reveals that significant shifts occurred between the trees and shrubs (Figure 6), most notably a decline in *Corylus avellana*-type and an increase in *Quercus*, *Betula*, *Alnus* and *Ulmus* and their reversal at ~1950 BC (320 cm), which coincides with the onset of mining in the area based on archaeological evidence (Timberlake, 2006; Mighall et al., 2009). Taxa associated with disturbance and pasture are recorded throughout zone CF1, albeit in low amounts, which makes the evidence for human activity circumspect. If land was used for grazing, this activity did not produce a significant change in herbaceous taxa or overall woodland cover. Several small peaks in microscopic charcoal suggest that fire might have been used to clear small areas of woodland periodically (including around ~2400 BC) or people exploited natural openings.

LPAZ CF1c (~2030 BC to c. 1630 BC) encompasses the age of range of the early mines in central Wales (between 1900 and 1700 Cal BC) (Timberlake, 2006) as well as the known early mines/prospecting sites more local to Cors Fochno. Of these, the oldest local workings date to 3390±35 year BP (1860-1530 BC) at Llancynfelin (Timberlake, 2003b), whereas a radiocarbon date of 3800±40 years BP (2340-2130 BC) came from a sample of charcoal from the base of a mine spoil tip close to some stone hammers located at the eastern workings of Erglodd mine on the south eastern edge of Cors Fochno, less than 2 km from the coring site (Figure 1b). The rAs records do not show evidence of metal pollution during this phase, but rPb has a possible minor peak and rZn shows a moderate increase from c. 2670 to c. 1700 BC (Figure 7). In contrast a small Pb peak was reported by Mighall et al. (2009).

Notwithstanding the occasional reversal, total tree pollen percentages suggest that woodland clearance occurred between 1900 and 1700 BC. Clear impacts are recorded on individual taxa: for example, *Quercus, Betula* and *Alnus* although *Corylus avellana*-type increases. LOI also dips at 338 and 318 cm (Figure 3). The presence of cereal-type pollen and a suite of non-arboreal taxa often associated with pasture and disturbed ground (described earlier) suggest that land was also cultivated and used for pasture. Fire could have been used to clear woodland to create agricultural land or as a result of burnt mound activity. By c. 1690 BC, regeneration of woodland took place. Overall, changes to vegetation during the period of prehistoric mining/prospecting are not considered to be significant according to the changepoint analysis (Figure 6).

The archaeological evidence clearly shows that people were present around Cors Fochno during the Bronze Age, which commences at approximately 324 cm in the pollen record. Several Bronze Age funerary and ritual sites, including the round barrows of Bedd Taliesin and Ynys Tudur, the Tre Taliesin standing stone and several burnt mounds, possibly Bronze Age, surround the bog (Page et al., 2012). A Bronze Age trough, made from oak, has also been dated to 1630–1380 BC and 1690–1430 BC (Page et al., 2012). A wattle walkway dated to between 4000 (321 cm) and 3100 (270 cm) BP, and human and animal fossilised footprints including cattle, sheep or goat and possibly a bear, that may date back to the Bronze Age, have been found in the peat at Borth and beach deposits at Ceredigion respectively. Consistent with these findings, both rPb and rAs point to increased metal deposition at Cors Fochno between c. 1500 and 1000 BC (Figure 7). Mighall et al (2009) reported a slightly different pattern with Pb and Cu increasing gradually from c. 1600 BC to peak c. 485 BC but both records suggest increased metal pollution at this time. At present there is no archaeological evidence for mining and smelting for this time period but As is contained within the mineral freibergite (which also contains Cu and it is intimately associated with galena), and is part of the local orefield. Arsenopyrite is also commonly associated with pyrite, galena, chalcopyrite and sphalerite and can be found on the fringes of the Snowdonia copper orefield and in the Central Wales orefield (Raybould, 1974; Bick, 1982). The only known operational copper mine in Wales during the mid-late Bronze Age was at Great Orme, Llandudno (Dutton et al., 1994).

Changepoint analysis suggests that a significant change occurred in vegetation at around 1000 BC, when more widespread soil erosion is also pointed out by the geochemical proxies, particularly reflected in CP3 (Figure 4). This marks the start of an increased and sustained deposition of more regional dusts and a phase of permanent woodland clearance surrounding Cors Fochno, seemingly unconnected to mining and/or smelting, during the late Bronze Age (from 279 cm 250 cm; c. 1280 to 910 BC). Archaeological evidence confirms that people were present in the area during this time. A wooden trough, found on the southern margins of the bog at Llangynfelin, has been dated to 1210-1280 Cal BC (Page et al., 2012) but confirmed Later Bronze Age settlements are still absent from Ceredigion (Driver, 2013). Clearance may also have been associated with hillfort building in Wales during the Late Bronze and Iron Ages (Driver, 2013). Iron Age hillforts and defended settlements are common in west Wales, although these types of site are absent around Cors Fochno apart from a small cropmark enclosure at Ynys Capel, which may be an Iron Age or medieval enclosed settlement (Poucher, 2009; Page et al., 2012). A univallate hillfort was constructed at Pen Dinas, Aberystwyth (Driver, 2013) and Middle to Late Iron Age dates have been obtained from the main rampart at Darren hillfort (Timberlake, 2007). Increased population in the lowlands may have also exerted greater pressure on land if upland areas were abandoned as a result of climatic deterioration during the Late Bronze Age. However, there is no noticeable change in the abundance of anthropogenic indicators in the Cors Fochno pollen record to suggest that land use intensified at this time around the bog but tree cover appears to have been in decline until (c. 600 BC) accompanied by a shift in Cp1 factor scores and a lower LOI (Figures 3 and 4). A short-lived phase of woodland regeneration occurs before clearance (predominantly hazel) is renewed in the Early Iron Age, c. 520 BC, which continues into the Roman period. This pattern is consistent with renewed tree clearance at Tregaron, c. 450 BC, and widespread clearance between the fifth to first centuries BC in North Ceredigion with the development of multivallate hillforts in the last two centuries BC (Driver, 2013).

During the late Bronze Age and Iron Age, the record of Cors Fochno atmospheric metal pollution (Figure 7) suggests a diverse use of metals: rPb is elevated between c. 710-550 BC, rZn between c. 540-350 BC, rPb and rAs by c. 230 BC, and rZn and rAs by c. 30 BC. Whether this represents pollution generated from local metal extraction or metallurgy is still contestable as there is a lack of local Iron Age archaeological evidence for lead working although the geochemical evidence is consistent with the previous lead record from the same site (Mighall et al., 2009). This compares favourably with evidence from elsewhere in Britain and Europe concerning the possible rise of a lead mining/metallurgical industry during the Late Iron Age, which culminated in the Roman period (e.g. Renberg et al., 2001; De Vleeschouwer et al. 2010). This includes sites in the British Isles: north-west and south west England (Le Roux et al. 2004; Meharg et. al., 2012), central Wales (Mighall et al., 2002b), at Flanders Moss in central Scotland (Cloy et al., 2005, 2008) and Raeburn Flow in southern Scotland (Küttner et al., 2014). Changepoint analysis suggests that a significant change in vegetation occurred c. 500 BC, seemingly unassociated with mining or metallurgy, but coincident with a large, permanent decline of *Corylus*. A change in land use might have been responsible with *Plantago lanceolata* recorded more regularly with higher percentages and a gradual rise in Poaceae. Cereal-type pollen was recorded intermittently. LOI values decreased and the Cp1 scores showed a slight gradual increase during this period of deforestation, both indicative of soil erosion (Figures 3, 4). This trend is also apparent in the concentrations of the individual elements (e.g. Rb and to a lesser extent, Al, Si and Ti; Supplementary Figure 2a). At a more regional scale, soil erosion remains high although possibly by shifting in area, as suggested by the see-saw pattern in Cp3 scores (Figure 4).

The Romans invaded Wales between AD 43 and AD 78 (Moore, 1968) and apparently accelerated the clearance of woodland that had commenced much earlier (see above). Several Roman forts were established in Ceredigion (Driver, 2013). A 1st century AD smelting complex was operational on the fringe of the Cors Fochno approximately 500 metres from the Flavin period Roman Fort (Timberlake, 2006; Page et al., 2012; Figure 1). The five dates from the industrial waste range from 90 BC through to AD 240, all overlapping between cal. AD 50–90 (Page et al., 2012) which is consistent with the radiocarbon dated Pb pollution at Cors Fochno reported by Mighall et al. (2009), lead enrichment in another core from the bog dated to between 110 BC to AD 180 (Page et al., 2012) and the peak in rPb recorded at c. AD 40 and 100 in this study. It is likely that lead smelting began in the late prehistoric period and continued until the early/mid-second century AD. From c. AD 74 through to AD 120–140 production may have been entirely under Roman military control (Page et al., 2012). If lead smelting did take place from c. 420 BC through the early part of the Roman occupation (until c. AD 140), it took place during a period of relatively rapid clearance of hazel woodland/scrub and more widespread clearance from c. 145 BC, followed by a phase of rapid woodland regeneration from c. AD 210. Changes in vegetation at this time are identified as significant in the changepoint analysis with spikes at c. AD 0 and AD 200 framing the decline and recovery of woodland (Figure 6). Charcoal recovered from the smelting site was dominated by oak although the results suggest that a wide range of species were used from the surrounding area as fuel, including *Betula* spp., *Corylus avellana* and *Alnus glutinosa* (Page et al., 2012). The use of local wood as a fuel is attested by the palaeoenvironmental analysis, which records a reduction in oak, alder and hazel in both Caseldine's pollen diagrams (in Page et al., 2012) and this study (LPAZ CF4). Woodland clearance during the first part of the Roman occupation resulted in increased soil erosion at both local and regional scales, as attested by peaking Cp1 and Cp3 scores (Figure 4).

Woodland regeneration continued into medieval times and a similar pattern is observed at other sites across Wales (see Moore, 1968; Page et al., 2012). A recovery of tree and shrub percentages can be seen in other pollen diagrams from Cors Fochno as well (Figure 5a; LPAZ

CF5; and in Page et al., 2012) and at Tregaron Bog after a Roman fort nearby was decommissioned between AD 130 and 170. An increase in oak and alder, concomitant with a decline in taxa associated with agriculture, characterised the late Roman period (Hughes et al., 2007). Woodland cover remained relatively stable at Cors Fochno as total arboreal pollen percentages fluctuated around 40% TLP into the early medieval period. Local soil erosion was low for most of this phase but sharply increased at the end (Cp1, Figure 4). The opposite seems to have occurred at a regional scale, as erosion remained high until c. AD 1000 and then suddenly decreased (Cp3, Figure 4).

Radiocarbon determinations and dendrochronological dates show that the timber trackway placed across part of Cors Fochno was constructed in the early- to mid-eleventh century AD with timbers replaced up to or soon after AD 1136 (Page et al., 2012). The final major phase of woodland clearance (end of LPAZ CF5, start of LPAZ CF6) broadly coincides with the Cistercian Strata Florida Abbey which was founded in AD 1165 until its dissolution by Henry VIII between AD 1536 and 1540. Increased dust deposition on to the bog surface is suggested by the high Cp1 scores (c. AD 1160-1420) and an initial decrease in LOI percentages (Figure 3). The shift in the Cp3 scores suggests the dust is mostly derived from local sources with a higher felsic component (Figure 4). Changes in vegetation at this time are identified as significant (Figure 6; c. AD 1200 & 1375). From c. AD 1145 onwards tree and shrub pollen percentages decline rapidly until c. AD 1380 and then more gradually. Edward I also ordered that all woodland be cleared in AD 1280 to remove safe havens for thieves and rebels (Moore, 1968). As a consequence, Moore (1968) suggests that these instructions may well have prompted the demise of alder in valley and lowland woods: *Alnus* pollen declines at Cors Fochno at this time. Direct archaeological evidence for occupation and exploitation in the area surrounding the bog is scarce after the Romans (Page et al., 2012). Page et al. (2012: 290) suggest that Llangynfelin parish church originated in the early medieval period and that a church was established by the fourteenth century, as were several small settlements, the occupants of which were probably engaged in agriculture and small-scale metal mining. By AD 1375, there was an increase in lead deposition and therefore the changes in vegetation, regarded as significant, can be linked to mining and metallurgy as well as an intensification of agriculture.

The total arboreal pollen percentage reached its lowest point for four millennia at c. AD 1900 (10 cm) implying widespread clearance until the planting of commercial forestry over the last 100 years. The rise in cereal-type pollen towards the end of LPAZ 5 is consistent with the increased importance of agriculture from the construction of the Abbey and culminating during the Napoleonic wars (1799-1815) (Moore, 1968). The Cp1 and Cp3 scores suggest that atmospheric dust deposition into the bog was at its highest level in the first half of the AD 20th century (Figure 4).

6.2: Towards a model for the environmental impact of mining and metallurgy: Pollen records close to Bronze Age copper mines in Wales and Ireland indicate that woodland disturbance was small-scale and non-permanent (Mighall & Chambers, 1993; Mighall et al., 2000; 2004; 2010; 2012), characteristics also shared with prehistoric ironworking sites (Chambers and Lageard, 1993; Mighall and Chambers, 1997). At Cors Fochno, the pattern of tree pollen is slightly different. Notwithstanding the occasional reversal, total tree pollen percentages continued to decline between c. 1900 and 1700 BC. Clear impacts are recorded on individual taxa. This might be because the Cors Fochno pollen data represents a regional record and it could be the result of woodland exploitation associated with numerous mines and/or prospecting sites (Timberlake, 2009). Woodland does recover to pre-mining levels (based on pollen percentages) and this evidence is consistent with the idea that mining and metallurgical activities in Bronze Age Britain and Ireland did not have a significant or long-lasting impact on woodland cover (Mighall et al., 2004; 2010; 2012). In the mining region of Falkenstein, near Schwaz in the Tyrol, Austria, Breitenlechner et al. (2010) also suggested prehistoric copper mining did not lead to large scale deforestation. At Kitzbühel, two episodes of forest clearance coincided with increasing heavy metal values but the forest regenerated thereafter (Viehweider et al. 2015). Hints of Early Bronze Age mining at Brixlegg do not seem to be of sufficient intensity to register in the pollen diagram but later mining in the Late Bronze Age caused small clearances and adversely affected the most abundant trees, but once mining activities cease there is some evidence for forest regeneration (Breitenlechner et al., 2013). Jouffroy-Bapicot et al. (2007) suggest that selective forest clearance and metallurgic contamination caused by local mining is closely connected at sites in the Massif Central and Basque Country but here too woodland regenerated. At Morvan (Massif Central) metallurgic activity during the Mid-Bronze Age led to modifications in plant cover but total percentages of arboreal pollen were not dramatically altered. Similar observations are made based on pollen records at Mont Lozère (Massif Central) and Quinto Real in the Basque Country, where tree taxa percentages decline associated with a concomitant increase in lead concentrations during the Bronze and Iron Ages. As pressure from metallurgical activities diminished (reflected by a decrease in Pb), total arboreal taxa recover to values similar to those recorded although forest composition was modified. Whilst *Fagus* was exploited for ore smelting in prehistory in

Bavaria, Küster and Rehfuess (1997) suggest that such activities did not cause deforestation but rather episodic declines of beech.

Another possible diagnostic indicator of prehistoric mining is evidence of firesetting. Firesetting could be represented in the palaeoecological record by increased values of microscopic charcoal. Assuming the tree clearance was primarily driven by mining, the peaks in microscopic charcoal recorded at Cors Fochno during the Bronze Age could also be associated with firesetting as they correlate with the dates of known prehistoric mines in the vicinity of the bog (Figure 6; LPAZ CF1b) but the scale of mining at this time was small-scale and akin to prospecting. Pyrophytic taxa such as *Calluna* and *Pteridium* do not show an immediate response suggesting that the charcoal was not derived from natural fires on the bog surface. The presence of cereal-type pollen and a suite of non-arboreal taxa often associated with pasture and disturbed ground suggest that land was also cultivated and used for pasture so the use of fire to clear woodland could have produced the increases in the microscopic charcoal. The evidence elsewhere is also circumspect. At Copa Hill microscopic charcoal only peaks towards the end of the presumed period of prehistoric mining (Mighall & Chambers, 1993). Because the pattern of microscopic charcoal records is very variable in palaeoenvironmental archives during the known periods of prehistoric mining, it may not be a reliable indicator of firesetting.

Woodland clearance re-commenced during the late Iron Age corresponding with renewed atmospheric pollution both of which culminated in Roman times, as has been identified at numerous sites in Britain and Europe (see references herein). These impacts were normally larger in scale compared to the Bronze Age but were also non-permanent with woodland regeneration often occurring as the Roman Empire collapsed. The evidence from Cors Fochno follows this pattern. However, there are slight differences. Forest clearance took much longer to recover (and not to pre-Roman values based on the pollen record) and forests were permanently modified in Morvan (Jouffroy-Bapicot et al., 2007). In contrast, at La Molina in NW Iberia, the impact on vegetation appears to be more similar to that described for prehistoric times with a series of short-lived declines in woodland followed by regeneration (López-Merino et al., 2014). Forest clearance was detected during Roman times and considered not to be associated with mining as heavy metal concentrations did not increase in tandem with decreased arboreal pollen at Kitzbühel and at Brixlegg (Breitenlechner et al., 2013; Viehweider et al., 2015).

Whilst forest cover showed a degree of resilience during the earliest phases of mining and metallurgy, selective deforestation and possible selectivity of trees for specific purposes and changes to the composition of woodland has often been suggested (e.g. the use of pine at the Bronze Age Mount Gabriel copper mines; O'Brien, 1990). Although in some cases selectivity is evident in the archaeological and palaeoecological record, the choice of wood for industrial use seems to predominantly reflect local availability and woodland composition (e.g. Mighall and Chambers, 1993, 2000). This is also observed at Cors Fochno and other sites analysed in Wales. Similar observations have been made in mining regions across Europe. The exploitation of *Fagus* appears to have been preferentially selected but it was the dominant tree in the forest surrounding Morvan and at Mont Lozère (Jouffroy-Bapicot et al., 2007) and in Southern Bavaria, Germany (Küster & Rehfuess, 1997). *Quercus* was favoured for charcoal production in the High Aldudes valley (Galop et al., 2001). Overall forest cover was maintained or recovered at all the sites. Similar examples also occur for ferrous sites in prehistory (e.g. Mighall and Chambers, 1997) and during Medieval times (Crew & Mighall, 2013). Exploitation of the dominant trees in forests and woodlands, whether preferentially or not, also altered their composition. Examples are mainly seen in Europe including the mining regions of Austria (Breitenlechner et al., 2010, 2013; Viehweider et al., 2015) France and the Basque Country (Jouffroy-Bapicot et al., 2007). Changes in woodland composition are less obvious at Cors Fochno and Copa Hill in Wales, in the Northern Pennines (Mighall et al, 2004) and Mount Gabriel in Ireland (Mighall & Chambers, 1993; Mighall et al., 2000).

7. Conclusions

1. At Cors Fochno, changepoint analysis suggests prehistoric mining and/or metallurgical activities did not appear to have a significant impact on vegetation. This could be because the sites surrounding the bog were examined by prospectors rather than mined on any significant scale. Further sites need to be analysed to see if this is typical.
2. The conceptual model of small-scale, non-permanent impacts on vegetation at times of prehistoric mining appears to be consistent across regions with evidence of early mining and metallurgy. If the impact on woodland had greater longevity, once activities ceased woodlands still recovered.
3. In contrast, changes in vegetation at Cors Fochno during Roman times were significant, particularly woodland clearance, and coincided with increased metal deposition on the bog. Any decrease that occurred during an episode of prehistoric and/or Roman mining/metallurgy was followed by regeneration when activities ceased, although woodland recovery is also seen in non-mining areas as well. The

Roman period is the first time that mining and metallurgy appears to have had a significant impact on vegetation surrounding Cors Fochno. In contrast, the results from La Molinia (NW Spain), for example, show a slightly different pattern in the pollen record, and more fine resolution studies could provide even further insights into the relationship between early mining and metallurgy and its impact on vegetation.

4. Overall, the results indicate that woodland/forest cover had a degree of resilience to mining and metallurgy in terms of total cover but there are examples whereby the most abundant trees in forest/woodland appeared to be adversely affected and some selectivity of trees seems to have taken place. There is evidence to suggest forest composition changed as a result of mining/metallurgy especially in mining regions on mainland Europe as the miners and metallurgists primarily targeted the most abundant tree species in the vicinity of the mines.
5. Microscopic charcoal records are not reliable indicators of firesetting, but peaks in the Cors Fochno record do correlate with archaeological evidence for prehistoric mining or prospection.

Acknowledgements

Toby Driver kindly provided information about the archaeology of the region. Jenny Johnson and Jamie Bowie drew the figures. Ed Schofield commented upon on an earlier draft of the manuscript. Permission to core Cors Fochno was provided by Mike Bailey (CCW). This project was funded by The Leverhulme Trust, grant number F/00/732/C and support from Cambria Archaeology. The comments from two reviewers helped to improve the manuscript.

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Figure captions

Figure 1: Location of the study area of Cors Fochno (Borth Bog), North West Wales, showing A. Location in the UK; B. detailed map of the Erglodd mine and Roman lead smelting site; C. the location of the sampling site and mining archaeology.

Figure 2: Age-depth curve for the Cors Fochno core. Model constructed in Clam using a smooth spline.

Figure 3: LOI profile for the Cors Fochno core.

Figure 4: Records of factors scores for the first four principal components.

Figure 5. Percentage microfossil diagram for selected taxa from Cors Fochno (a) trees, shrubs, spores, preservation and microscopic charcoal (b) herbs (c) non-pollen palynomorphs (NPPs).

Figure 6: Results from the inferred Changepoint analysis for the Cors Fochno pollen data. The weighted average model is shown as a solid red line, and the maximum likelihood model as a dashed black line. The gray filled area represents the statistical probability of a changepoint based on the posterior distribution for the model parameters (see Gallagher et al., 2011 for more details).

Figure 7: Detrended residual variance for Pb, Zn and As.

Table 1: Radiocarbon dates from Cors Fochno (Borth Bog).

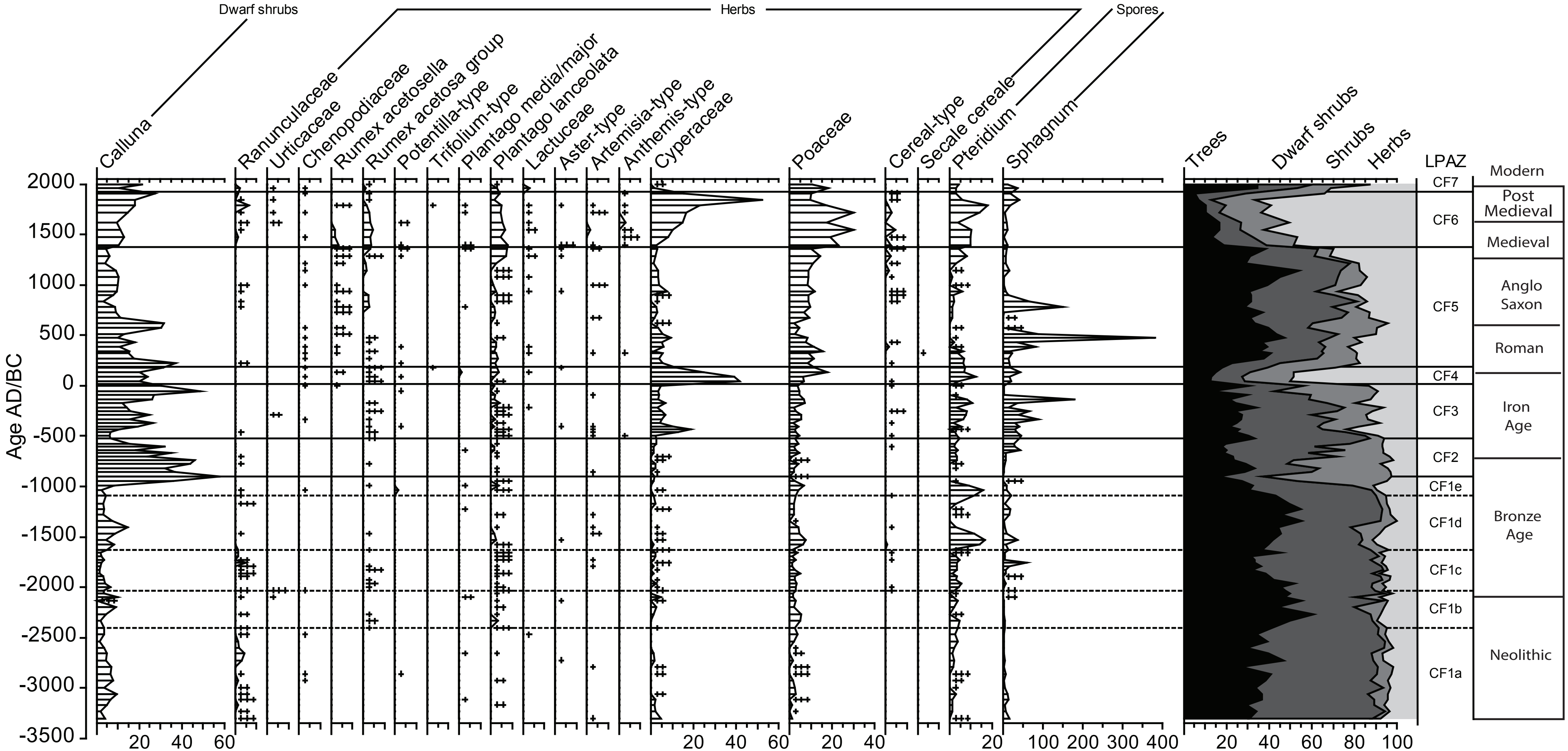
Table 2: Factor loadings from the PCA for the chemical elements from Cors Fochno.

Supplementary figure 1: PCA results of geochemical data (elemental composition). Percentage of explained variance (square of factor loadings) of the principal components extracted (diagonal lines – Cp1; pluses – Cp2; horizontal lines – Cp3; cross lines – Cp4).

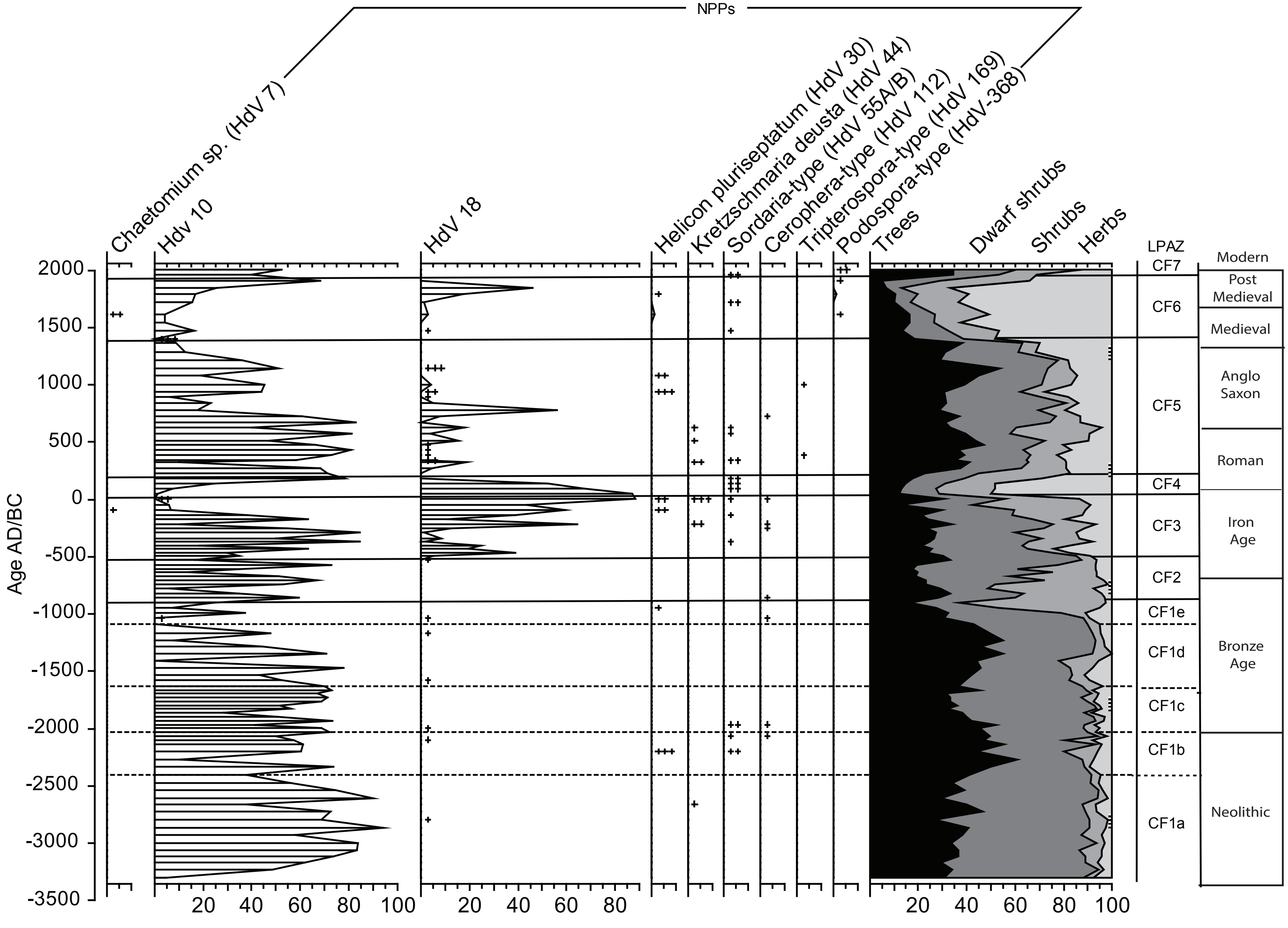
Supplementary figure 2a: Profiles for Si, Al, Ti and Rb from the Cors Fochno core

Supplementary figure 2b: Profiles for Pb, Zn, As and Fe from the Cors Fochno core.

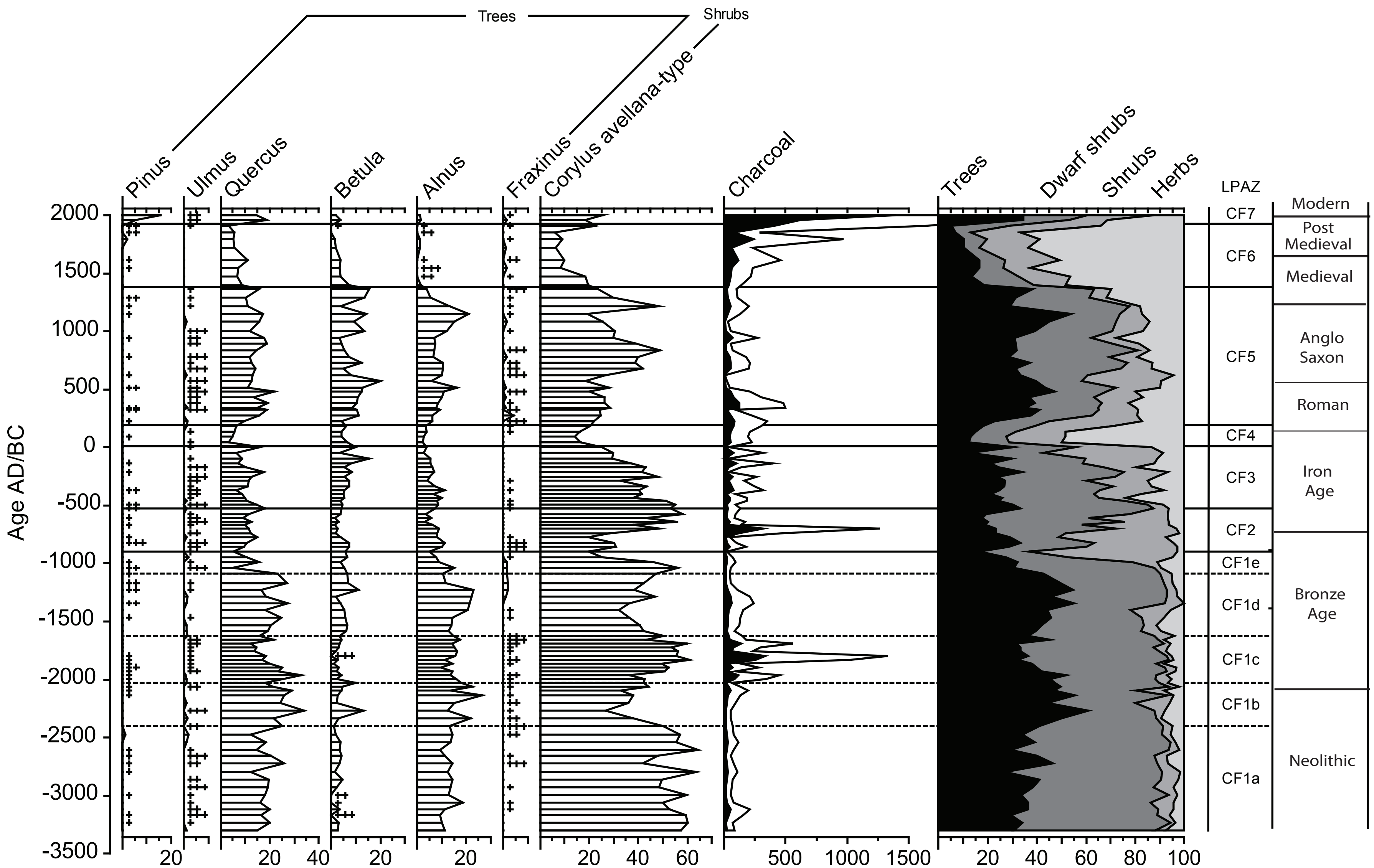
Supplementary figure 3. Percentage microfossil diagram for selected taxa from Cors Fochno (a) trees, shrubs, spores, preservation and microscopic charcoal (b) herbs (c) non-pollen palynomorphs (NPPs).



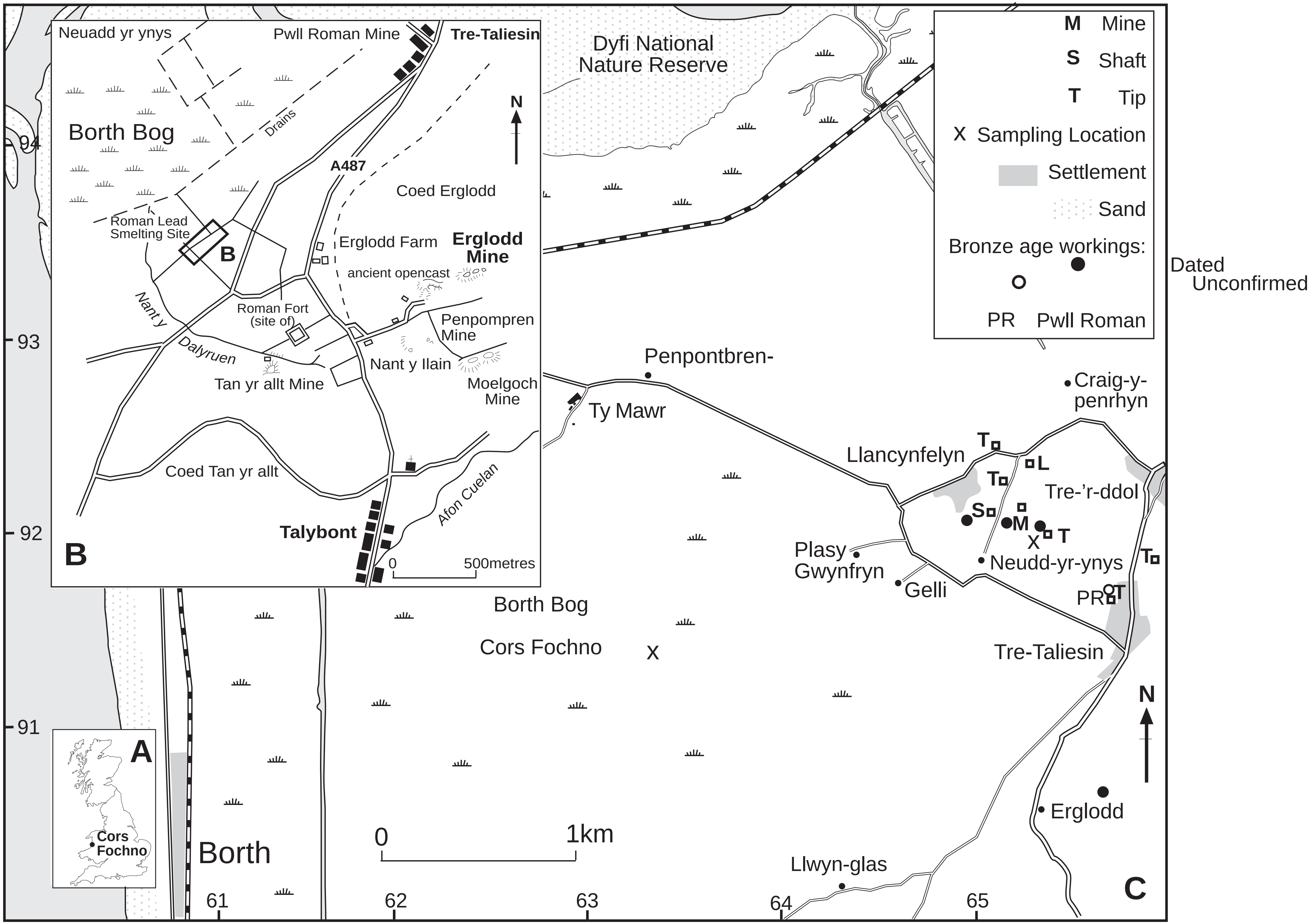
Dwarf shrubs
Herbs
Spores
Calluna
Ranunculaceae
Urticaceae
Chenopodiaceae
Rumex acetosella
Rumex acetosa group
Potentilla-type
Trifolium-type
Plantago media/major
Plantago lanceolata
Lactuceae
Aster-type
Artemisia-type
Anthemis-type
Cyperaceae
Poaceae
Cereal-type
Secale cereale
Pteridium
Sphagnum
Trees
Dwarf shrubs
Shrubs
Herbs
LPAZ
Age AD/BC
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
20 40 60
20 40 60
20 40
20
100 200 300 400
20 40 60 80 100
CF7
CF6
CF5
CF4
CF3
CF2
CF1e
CF1d
CF1c
CF1b
CF1a
Modern
Post Medieval
Medieval
Anglo Saxon
Roman
Iron Age
Bronze Age
Neolithic



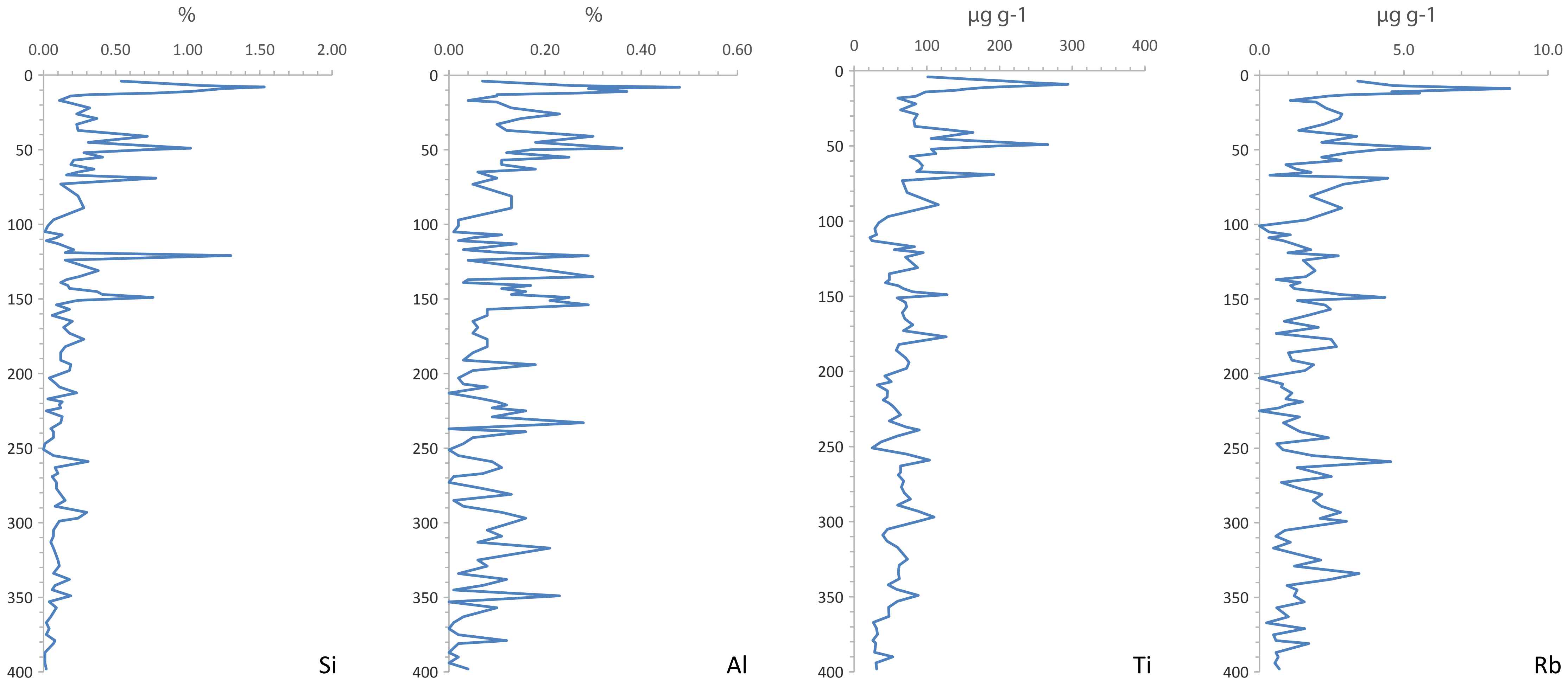
NPPs
Chaetomium sp. (HdV 7)
Hdv 10
HdV 18
Helicon pluriseptatum (HdV 30)
Kretzschmaria deusta (HdV 44)
Sordaria-type (HdV 55A/B)
Cerophera-type (HdV 112)
Tripterospora-type (HdV 169)
Podospora-type (HdV-368)
Trees
Dwarf shrubs
Shrubs
Herbs
LPAZ
CF7
CF6
CF5
CF4
CF3
CF2
CF1e
CF1d
CF1c
CF1b
CF1a
Modern
Post Medieval
Medieval
Anglo Saxon
Roman
Iron Age
Bronze Age
Neolithic
Age AD/BC



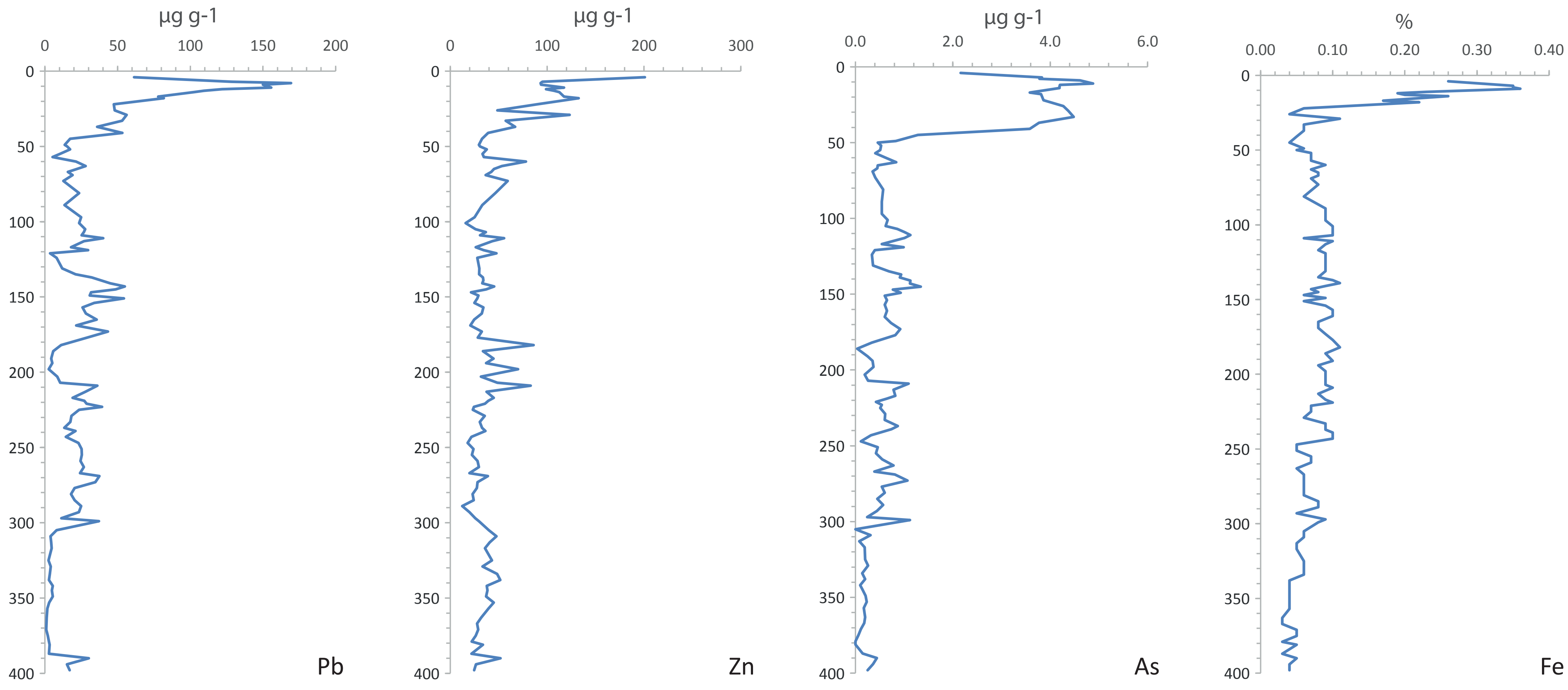
Trees
Shrubs
Pinus
Ulmus
Quercus
Betula
Alnus
Fraxinus
Corylus avellana-type
Charcoal
Trees
Dwarf shrubs
Shrubs
Herbs
LPAZ
Age AD/BC
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
20
20
40
20
20
20
40
60
500
1000
1500
20
40
60
80
100
CF7
CF6
CF5
CF4
CF3
CF2
CF1e
CF1d
CF1c
CF1b
CF1a
Modern
Post Medieval
Medieval
Anglo Saxon
Roman
Iron Age
Bronze Age
Neolithic



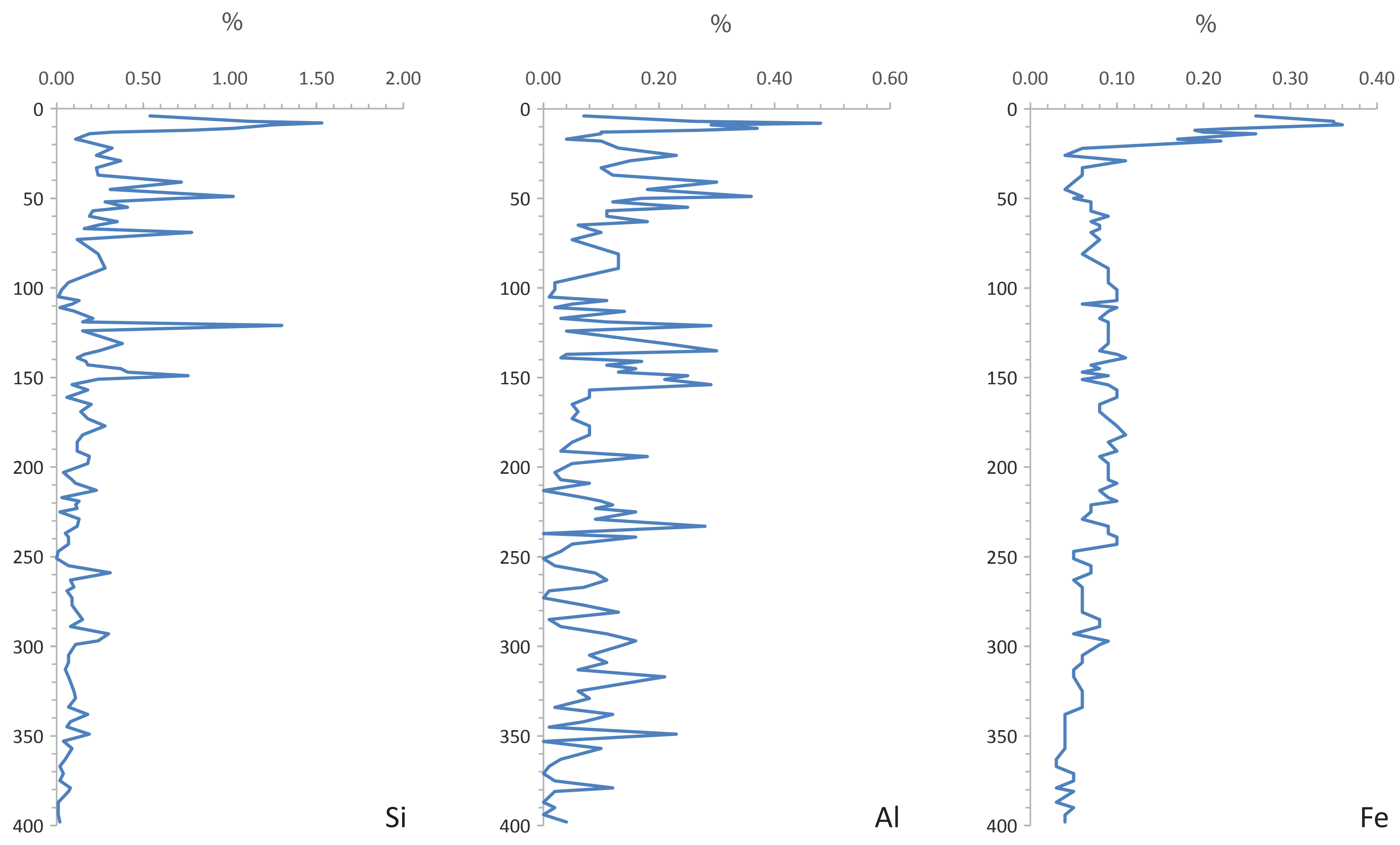
Neuadd yr ynys
Pwll Roman Mine
Tre-Taliesin
Borth Bog
Drains
A487
Coed Erglodd
Roman Lead
Smelting Site
B
Erglodd Farm
Erglodd
Mine
ancient opencast
Nant y
Dalyruen
Roman Fort
(site of)
Penpompren
Mine
Nant y Ilain
Moelgoch
Mine
Tan yr allt Mine
Coed Tan yr allt
Afon Cuelan
Talybont
0
500metres
N
Dyfi National
Nature Reserve
M Mine
S Shaft
T Tip
X Sampling Location
Settlement
Sand
Bronze age workings:
Dated
Unconfirmed
PR Pwll Roman
94
93
92
91
Penpontbren-
Ty Mawr
Craig-y-
penrhyn
Llancynfelyn
Tre-'r-ddol
Plasy
Gwynfryn
Gelli
Neudd-yr-ynys
Borth Bog
Cors Fochno
Tre-Taliesin
Erglodd
Borth
0
1km
Llwyn-glas
A
Cors
Fochno
C
61
62
63
64
65

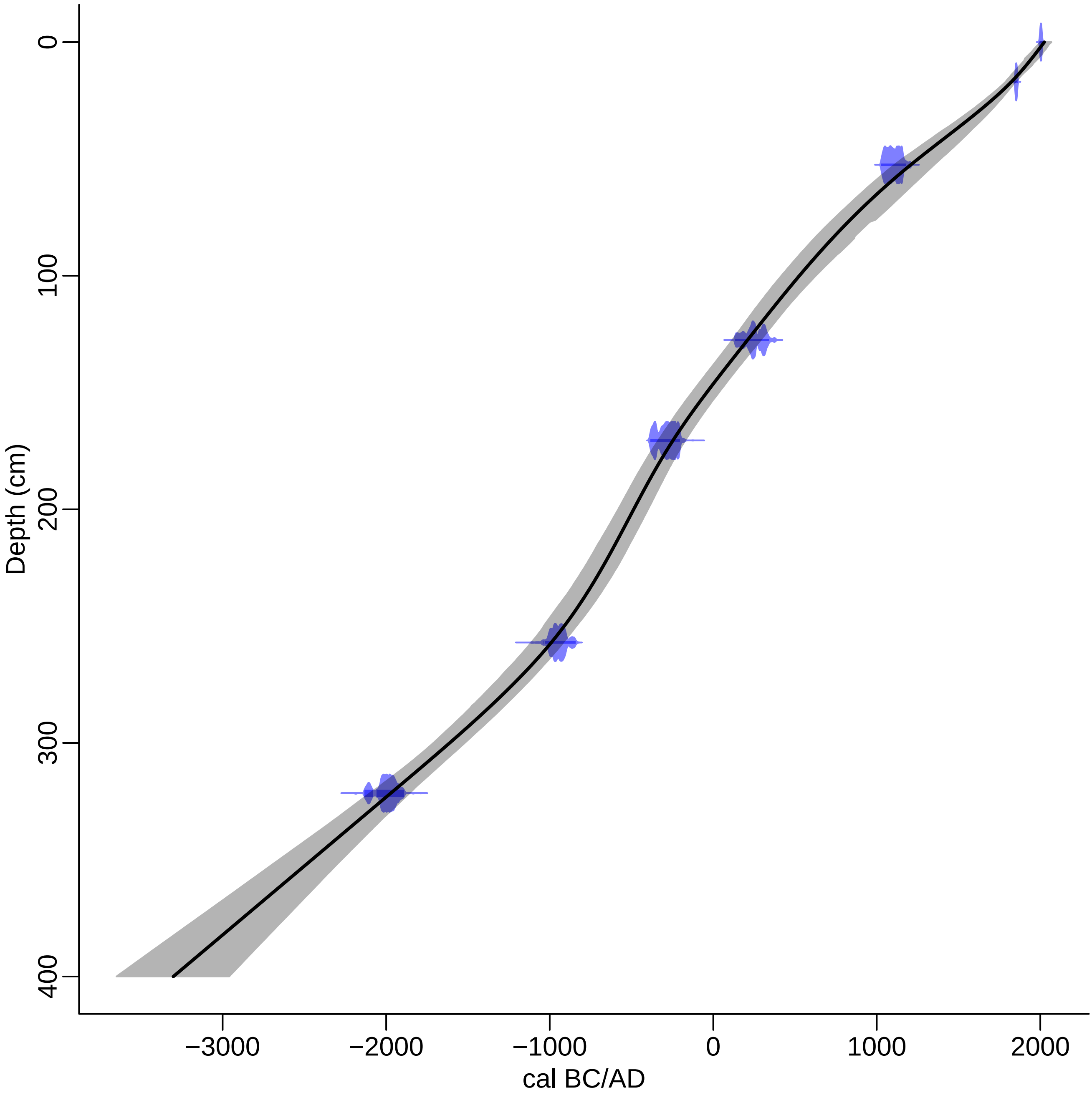


%
0.00
0.50
1.00
1.50
2.00
0
50
100
150
200
250
300
350
400
Si
%
0.00
0.20
0.40
0.60
Al
µg g-1
0
100
200
300
400
Ti
µg g-1
0.0
5.0
10.0
Rb

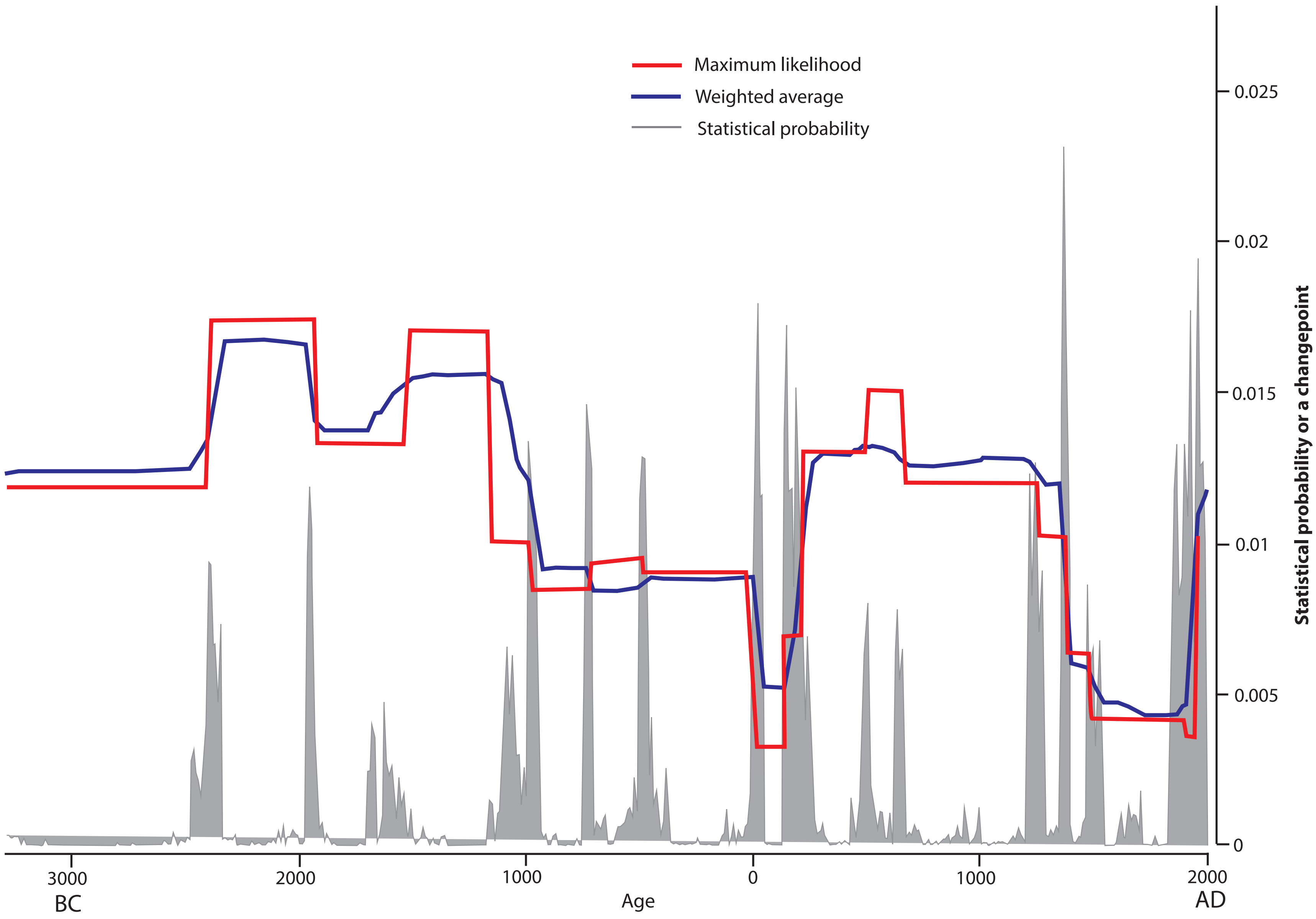


µg g-1
0
50
100
150
200
0
50
100
150
200
250
300
350
400
Pb
µg g-1
0
100
200
300
Zn
µg g-1
0.0
2.0
4.0
6.0
As
%
0.00
0.10
0.20
0.30
0.40
Fe

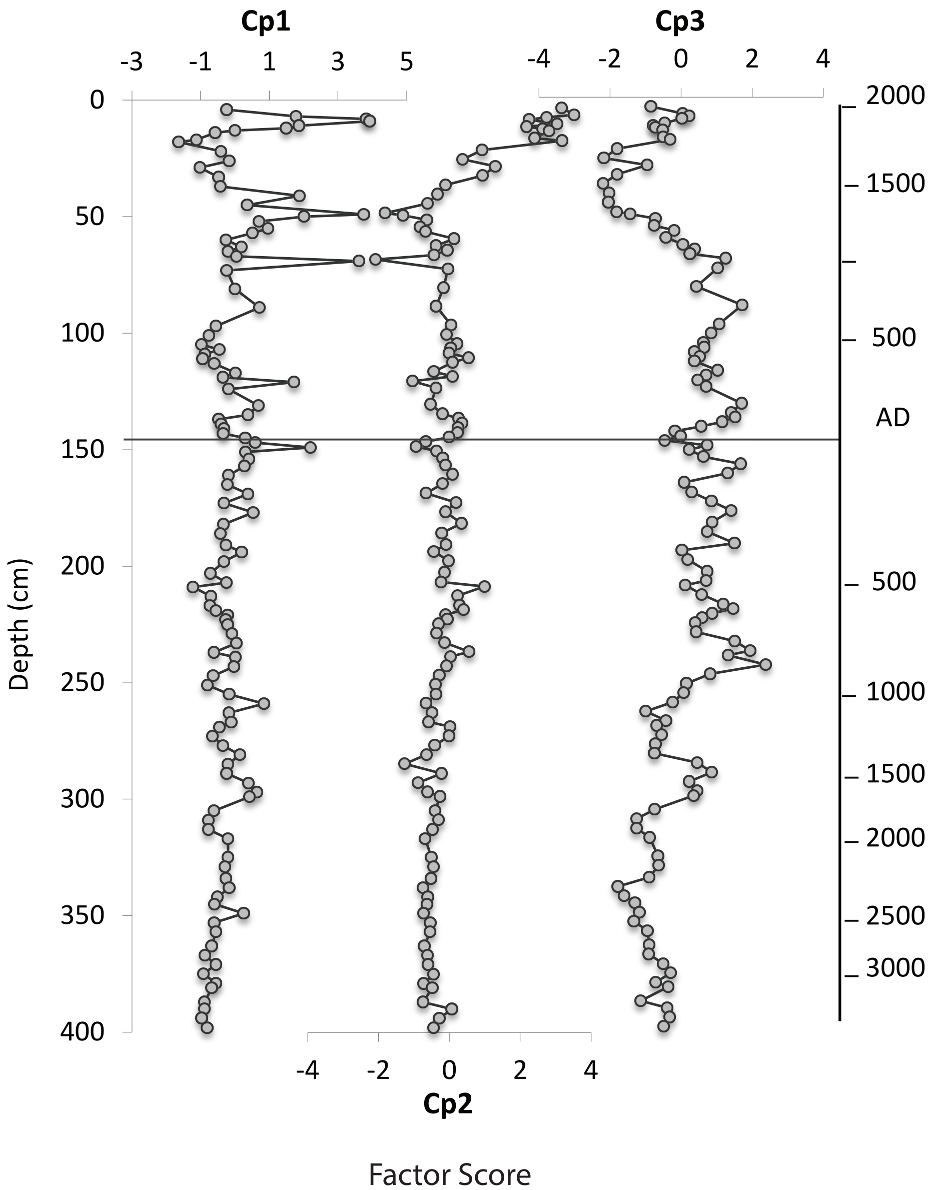

%
0.00 0.50 1.00 1.50 2.00
0
50
100
150
200
250
300
350
400
Si
%
0.00 0.20 0.40 0.60
0
50
100
150
200
250
300
350
400
Al
%
0.00 0.10 0.20 0.30 0.40
0
50
100
150
200
250
300
350
400
Fe



0
100
200
300
400
Depth (cm)
−3000
−2000
−1000
0
1000
2000
cal BC/AD



Maximum likelihood
Weighted average
Statistical probability
0.025
0.02
0.015
0.01
0.005
0
Statistical probability or a changepoint
3000
BC
2000
1000
Age
0
1000
2000
AD


Cp1
-3
-1
1
3
5
Cp3
-4
-2
0
2
4
0
50
100
150
200
250
300
350
400
Depth (cm)
2000
1500
500
AD
500
1000
1500
2000
2500
3000
-4
-2
0
2
4
Cp2
Factor Score

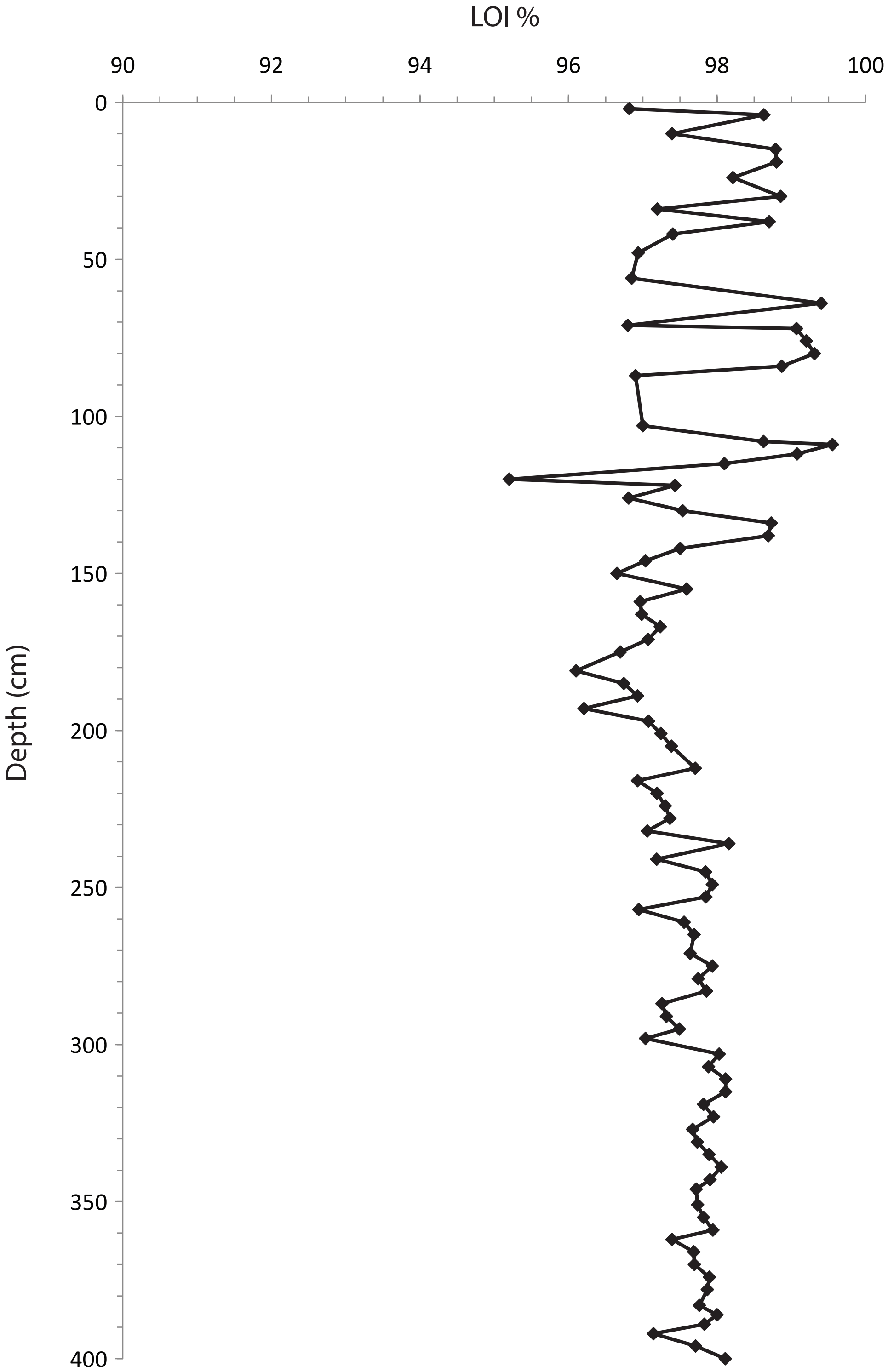

LOI %
90
92
94
96
98
100
Depth (cm)
0
50
100
150
200
250
300
350
400

Table 1: Radiocarbon dates from Cors Fochno (Borth Bog).

Laboratory no.	depth (cm)	uncalibrated date	calibrated age range (2 sigma)
Poz-25313	52-53	925±30	cal AD 1026-1181
Poz-17099	128-129	1780±35	cal AD 134-338
Poz-25314	170-171	2225±35	cal BC 381-203
Poz-25353	257-257.5	2795±35	cal BC 1025-842
Beta-180084	320-323	3630±40	cal BC 2133-2081; 2060-1892

	Cp1	Cp2	Cp3	Cp4
Ti	**0.90**	0.28	-0.14	0.12
Zr	**0.88**	0.06	0.01	0.20
Si	**0.87**	0.32	-0.10	0.12
Rb	**0.83**	0.30	-0.13	0.10
Al	**0.73**	0.20	-0.13	-0.04
Y	**0.72**	0.60	-0.13	0.09
K	**0.62**	0.49	-0.23	0.11
Fe	0.40	**0.85**	0.17	0.06
Pb	0.41	**0.84**	-0.06	-0.01
Zn	0.07	**0.82**	-0.24	0.20
As	0.26	**0.78**	-0.30	0.15
Cu	0.42	**0.77**	-0.11	0.19
Sr	-0.05	-0.05	**0.97**	-0.09
Ca	-0.33	-0.28	**0.87**	-0.15
Cr	0.19	0.09	-0.12	**0.90**
Ni	0.08	0.55	-0.14	**0.65**
Eigv	5.2	4.6	2.0	1.5
Var	32.4	28.7	12.8	9.1
aVar				83.1