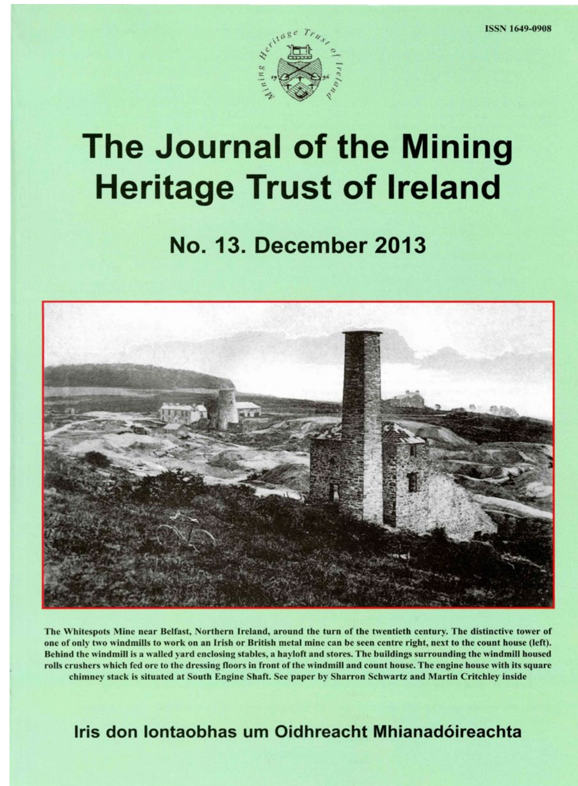

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A PALAEOECOLOGICAL ASSESSMENT OF THE IMPACT OF FORMER METAL MINING AT GLENDALOUGH, COUNTY WICKLOW IRELAND

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Abstract: This paper presents the preliminary findings of a palaeoecological and geochemical study of a peat core sampled to reconstruct the environmental history at Glendalough and Glendasan, County Wicklow, in order to search for signs of undocumented early metal mining. An increase in lead concentrations raises the intriguing possibility of mining in the Glendalough area from the eleventh century onwards and in particular, a rapid growth from the fifteenth century. This phase of increased lead pollution coincides with the gradual loss of woodland in the area. *Journal of the Mining Heritage Trust of Ireland, 13, 2013, 9-22.*

INTRODUCTION

This paper presents the preliminary findings of a palaeoecological and geochemical study of a peat core sampled to reconstruct the environmental history at Glendalough and Glendasan, County Wicklow. The work formed part of the *Metal Links: Forging Communities Together* InterReg IVA project which deals with mining communities in Wales (Mid-Wales and Anglesey) and Ireland (Glendalough and Copper Coast, County Waterford). All of these areas were mined extensively during the nineteenth century for lead and copper, with the lead mines at Glendalough and Glendasan being the most important nineteenth century lead producers in Ireland (Schwartz and Critchley 2012, 5). However, archaeological investigations in Wales and England (Timberlake 2009) have demonstrated that metalliferous mining, principally for copper ores, started as far back as the Bronze Age in some areas. In Ireland, with the exception of the Bronze Age copper mines of Ross Island near Killarney and South West Cork (O'Brien 2004; 1994), there has been very little scientific investigation of early metal mining. References to 'Danes workings' appear in eighteenth and nineteenth works of reference (for example, O'Halloran 1772, notes the Ross Island Mines were widely believed to be the work of the 'Danes') yet no evidence is given for their dating.

At Glendalough, the co-location of lead-zinc mineralisation with the monastic settlement of St Kevin (also known as the Seven Churches), founded in the sixth century and which attained its zenith between the tenth and twelfth centuries, raises the intriguing possibility of a probable link between the Monastic City and the working of metallic minerals (see Fig. 1). Undisturbed and slowly accumulating peat can preserve a record of particles (such as pollen, charcoal and mineral dust) which fall from the air onto its surface and are buried by subsequent layers of peat. So, in the context of possible pre-nineteenth century mining at Glendalough and a link with the monastic settlement, the *Metal Links* project funded the acquisition and analysis of a peat core obtained from an ombrotrophic (rain-fed only) blanket bog in the vicinity of the Glendalough/Glendasan mines in the uplands of County Wicklow.

The aims of the research were threefold. Firstly, to reconstruct the vegetation and fire history from the peat core through the use of microfossil (pollen, non-pollen palynomorphs [fungal spores (NPPs)] and microscopic charcoal analysis. Secondly, to construct a chronology for the sequences using radiocarbon dating and thirdly, to reconstruct atmospheric dust and metal pollution histories using peat geochemistry.

GEOLOGY, MINERALISATION AND KNOWN MINING HISTORY

The underlying geology of the Glendalough area is over 400 million years old and was formed during the Caledonian orogeny (Phillips 2001). Around 430 million years ago, the area that became the Wicklow Mountains was situated on the fringes of an equatorial microcontinent to the south of the Iapetus Ocean named Avalonia. Mud, silt and mixed coarse-fine sediments from turbidity flows were deposited on the ocean floor and there was local volcanic activity giving rise to ash deposits, lavas and local igneous intrusions. As the continental plates moved towards each other, the Iapetus Ocean began to close and Avalonia drifted into northern latitudes, colliding first with the continent of Baltica and then with Laurentia to form the supercontinent of Euramerica. The Iapetus closed completely at the end of the Silurian period (443-415 million years ago). High pressure and high temperatures accompanied the closure, resulting in metamorphism of the ancient ocean sediments to form the slates and greywackes which now outcrop at Glendalough.

Around 400 million years ago (towards the end of Caledonian orogeny) the Wicklow Mountains were intruded by a granite

Fig. 1. ***The valleys of Glendalough (left)and Glendasan (right) with Camaderry Mountain between. The Monastic City of Glendalough can be seen centre right. The mine workings in Glendalough and Glendasan were joined by workings that extended right through Camaderry Mountain in the mid-nineteenth century. The peat core sample was taken from an area of rain fed blanket bog on the north west slope of Camaderry Mountain. Photograph with kind permission of the Glendalough Mining Heritage Project***

batholith, known as the Leinster Granite, the largest continuous area of granite in Ireland and Britain (O'Connor and Brück 1978). The heat generated by this process created an aureole of schists: metamorphosed slates and shales. Superheated fluids driven by the heat of the granite leached lead and other metals from the schists and deposited these along sub-vertical cracks in the granite close to the margin with the schists to form mineral lodes (McArdle *et al* 1978). The lodes are typically composed of galena (lead sulphide), lesser sphalerite (zinc sulphide) and minor pyrite (iron sulphide), chalcopyrite (copper sulphide) and native silver, along with rock of little or no commercial value such as quartz and barite. Repeated episodes of glaciation during the Quaternary (2.58 Ma to present), further weathered and sculpted the stumps of the Caledonian Mountains to reveal the Leinster granite which form the spine of the present day Wicklow Mountains. The relentless flow of glaciers exposed the mineral veins in the sides of the characteristic U-shaped valleys of Glendasan, Glendalough and Glenmalure and created the ribbon lakes in Glendalough and corries dammed by moraine such as Lough Nahanagan (Synge 1973).

The known lodes rarely show mineral or even gangue (friable quartz and siderite) at the surface, and where not masked by scree, moraine or bog, the hydrothermally altered and softened granite which accompanies the strong mineralisation weathers to noticeable depressions. The most visible evidence of a weathered lode is the South Luganure Lode uphill from the Old Luganure Adit, where a gully marks its course. It is likely than any pre-nineteenth century mining would have been undertaken only on visible outcrops in remote uplands areas such as this.

Current narratives of the Glendalough area in County Wicklow focus almost exclusively on its monastic heritage. Yet, from the thirteenth century, the area has been witness to significant industry that has had a profound impact on its geomorphology. In the seventeenth century, large iron smelting works were established in southern County Wicklow at Carnew, by Welshman, Calcott Chambre, who leased Carnew Castle in 1619 (History of Parliament). Protestant colonisers arrived in the southern part of the county during the second half of the seventeenth century to settle close to the forest of Shillelagh that was exploited for its vast quantities of oak as a source of charcoal; many of these immigrants were skilled specialists such as bellows makers, founders, finers and hammer men, who worked in the local ironworks to smelt the iron ore shipped from Bristol.

Around this time in Glendalough too, the need to supply charcoal for smelting works resulted in a 'smash and grab' operation where all available wood was felled for cordage, laying waste to the landscape by denuding it of its deciduous tree cover. Around 83 identified charcoal burning platforms

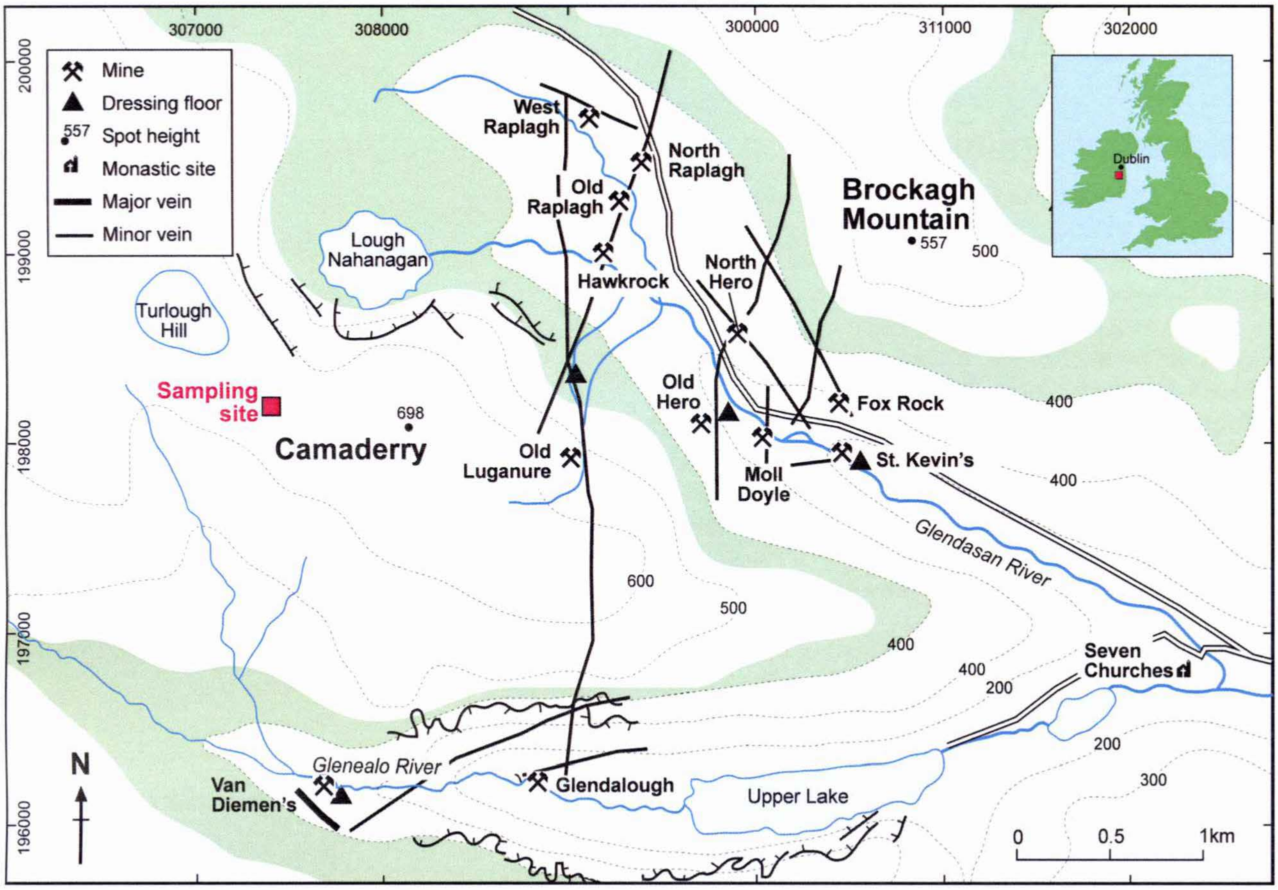

Fig. 2: ***The pollen sampling site and study area with principal mining features in the Wicklow Mountains***

thought to date from the 13th-18th centuries have been detected in Glendalough (McDermott *et al*, 2012) and signs of iron founding associated with pits and furnace debris were revealed during excavation for the OPW Visitor Centre, a site close to the Monastic City. The presence of potsherds enabled the ironworking to be dated to the thirteenth or fourteenth century (Manning, 1983).

In the neighbouring valley of Glenmalure, lead mining goes back to at least the mid-eighteenth century and probably earlier, as the workings of Ballinafunshoge on a map dated 1812 by geologist Thomas Weaver, depict extraction to a depth of approximately 60 fathoms (120 m) with large stoped out areas. Field study of the open cast workings (depicted on Weaver's plan) on the back of the lode in this valley seem to be of a particular early character and a water powered lead smelting works was set up in the eighteenth century to smelt the ore raised in the vicinity of the works. Fraser noted at the turn of the nineteenth century that a lode of lead had been discovered near the Seven Churches in Glendalough which probably refers to the activities of geologist, Thomas Weaver, a shareholder and resident manager of the Associated Irish Mine Company at Avoca (Fraser 1801, 14). He is credited with the discovery of the South Luganure Lode which he had commenced working in 1807 (Stephens 1812) forming a company to do so. However, on a plan dated to 1814, he named 'an old trial at head of Great Ravine on Luganure Vein' as well as an 'old drift' (located above First Adit in Glendalough), strongly suggesting that these workings predate his activity in the valley and are thus eighteenth century or earlier in derivation.

The main period of working occurred after the mines and lands were purchased from Weaver's company by the Mining Company of Ireland (MCI), 1824-1890. Over the course of the next six decades, the MCI would thoroughly explore their mineral sett known collectively as the Luganure Mines, opening numerous workings on several main lodes in Glendasan, including South Luganure, Ruplagh and West Ruphlagh, East and West Foxrock, Moll Doyle, Hero and North Hero. In the neighbouring valley of Glendalough, the South Luganure Lode that passed from Glendasan through Camaderry Mountain (a distance of around 2.5 km) was worked where it outcropped high up in the side of the mountain, eventually effecting a communication between both valleys. The Glendalough Lode and those at Van Diemen's Land, on the remote moorland in the Glenealo valley, were also exploited.

Following a decline in the price of lead in 1890 the mines and estate of Glendalough were purchased by J.B. Wynne of Ballybrophy. He focussed attention on the Whiterocks Adit in Glendalough where a small plant was also erected to rework the spoil heaps from the MCI era rich in sphalerite and galena and also the Foxrock Lode in neighbouring Glendasan. However, mining activity was stifled by a lack of capital following the British government's withdrawal of funding after WW1. It was not until the late 1940s that attention once more focussed on the mines which were reopened in the Glendasan valley, centred on the Moll Doyle and Foxrock

Lodes, where a gravity mill was erected to treat the ore. All practical mining ceased in 1957 (Schwartz and Critchley, forthcoming).

SAMPLE SITE DETAILS

A core was taken from an area of upland, ombrotrophic blanket bog (53°00'55.36"N - 6°22'51.18"W) at an elevation of *c.* 644 metres located west of Seven Churches in the Wicklow Mountains National Park. Here a series of eroded hags mark an area of blanket peat that extends north-west (53°01'12.06"N - 6°23'17.80"W) which are ideal to undertake a palaeoenvironmental study. The sampling site lies in close proximity to former mining areas located in the Glendalough and Glendasan valleys (Fig. 2); the charcoal making areas that surround the upper lake in both the Lugduff and Sevenchurches Townlands; the ringfort/Cashel in the Lugduff townland at Ballinacor south and the coring location is also relatively close to the standing stone on Cullentragh Mountain.

The study site is well suited to meet the aims of the project as it is close to historically important lead mines and the record preserved in this ombrotrophic bog should allow us to identify both local and regional records of vegetation change and palaeo-pollution over several millennia. Furthermore it will complement the findings of pollen-analytical studies undertaken in County Wicklow by Jessen (1949), Bowler and Bradshaw (1985), Mitchell and Conboy (1993), Cole and Mitchell (2003) and Leira *et al.* (2007).

METHODOLOGY

Field Sampling

Ideally, ombrotrophic peats, raised above the mineralised water table, are preferred to reconstruct past metal deposition histories as this environment only receives metal pollutants from the atmosphere and it minimises the risk of such post-depositional mobility (Shotyk, 1996). Therefore a 2 metre-deep core, named CAM, was taken from the blanket peat on the upland plateau close to the summit of Camaderry from the middle of an eroded peat hag (307398E 198167N). The core was collected on the 21st September 2012 using a 50 cm long, 8 cm wide Russian corer (Fig. 3). The cores were then wrapped in plastic, sealed and stored in a cold store.

Fig. 3: *Russian corer used to extract the peat sample*

Laboratory work

Laboratory analysis of the peat core was undertaken to determine the age of the core, geochemical composition and the abundance of microfossils of plants. Due to financial constraints, detailed analysis was only performed at discrete intervals down the peat profile to a depth of about 50 cm (dated *c.* AD 582).

Geochemistry: Elemental composition of the peat was determined after drying, milling and homogenizing the samples. Concentrations of major, minor and trace lithogenic elements (S-Sulphur, P-Phosphorous, Si-Silicon, Al-Aluminum, Fe-Iron, Ti-Titanium, Ca-Calcium, K-Potassium, Rb-Rubidium, Sr-Strontium, Zr-Zirconium), trace metals and metalloids (Cr-Chromium, Mn-Manganese, Ni-Nickel, Cu-Copper, Zn-Zinc, Pb-Lead), and halogens (Cl-Chlorine, Br-Bromine) were obtained by X-ray fluorescence dispersive EMMA-XRF analysis (Cheburkin and Shotyk, 1996; Weiss *et al.*, 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 1 g kg^{-1} for S, P, Al, Fe and Ti, 5 g kg^{-1} for Si, 0.5 µg g^{-1} (micrograms per gram of sample) for Pb, and 1 µg g^{-1} for the other trace elements. Replicate measurements were done in one every five samples in order to account for reproducibility; all replicates agreed within a 5%.

Microfossils: Samples of *c.* 2 g wet weight and 0.5 cm thickness were prepared for pollen and microscopic charcoal analyses using the procedure described by Barber (1976). In pollen preparations other microfossils of various origin are also preserved. Among the 'extra' microfossils in peat are spores of fungi, remains of algae and invertebrates and these are termed non-pollen palynomorphs (NPPs). The analysis procedure is quite laborious and involves sitting in a laboratory, at a microscope and counting and identifying the pollen grains, NPPs and charcoal fragments. At least 500 land pollen grains were counted for each sample. Pollen identification was made using the identification keys from Fægri *et al.* (1989), Moore *et al.* (1991) and pollen type slide collections housed in the University of Aberdeen and Headland Archaeology, Edinburgh. When possible, cereal-type pollen was differentiated from wild grass pollen based on grain size, pore and annulus diameter and surface sculpturing (Andersen, 1979). Pollen preservation was recorded following Cushing

Depth	Description
0-5 cm	surface vegetation, *Sphagnum* moss
5-18 cm	dark brown humified herbaceous peat, *Callunae* (heather) + ($Th^3$4 nig 3, sicc 2, strf 0)
18-50 cm	brown fibrous *Sphagnum* peat, *Callunae* (heather) + (Tb $Sphagni^2$4, nig 2.5, sicc 2, strf 0)
50-110 cm	dark brown humified herbaceous peat with *Calluna* (heather) rootlets ($Th^{2.5}$4 Callunae +, nig 2.5, sicc 2.5, strf 0)
110-154 cm	brown *Eriophorum (*cottongrass*)*-rich peat ($Th^{1.5}$4 nig 2.25, sicc 2.5, strf 0)
154-205 cm	dark brown humified herbaceous peat ($Th^{2.5}$4 nig 3, sicc 2.5, strf 1)
Base	grey clay (As^4 nig 1, sicc 2.5, strf 0)

Table 1: ***Stratigraphy of CAM peat core with details of main plant species, composition, degree of humification and physical properties. For abbreviations see Troels-Smith (1955)***

(1967) and each pollen grain was classified as broken, corroded, crushed or degraded. Pollen grains that had no remaining distinguishing features were categorised as unidentified. NPPs were recorded during routine pollen counting and they were identified using the descriptions and photomicrographs of van Geel (1978), van Geel *et al.*, (1989; 2003), van Geel and Aptroot (2006) and van Hoeve and Hendrikse (1998).

RESULTS

Stratigraphy: the stratigraphy of the CAM core is described below using the classification system devised by Troels-Smith (1955). Troels-Smith developed a comprehensive classification for sediments from organic-rich northern hemisphere temperate lakes and wetlands. The classification was originally designed primarily as a field based classification but has been expanded to include laboratory study. Troels-Smith's scheme defines three elements that should be specified for each layer of stratigraphy identified, these are:

- Composition or The Components
- The Degree of Humification
- The Physical properties of Sediment layer

Radiocarbon dating: Radiocarbon dating (or simply carbon dating) is a radiometric dating technique that uses the decay of carbon-14 (^{14}C) to estimate the age of organic materials, such as wood. The Earth's atmosphere contains various isotopes of carbon, roughly in constant proportions. These include the main stable isotope (^{12}C) and an unstable isotope (^{14}C) (Walker, 2005). Through photosynthesis, plants absorb both forms from carbon dioxide in the atmosphere (Bowman, 1990). When a plant dies, it contains the standard ratio of ^{14}C to ^{12}C, but as the ^{14}C decays with no possibility of replenishment, the proportion of carbon 14 decreases at a known constant rate. The time taken for it to reduce by half is known as the half-life of ^{14}C. The measurement of the remaining proportion of ^{14}C in organic matter thus gives an estimate of its age (a raw radiocarbon age) (Bowman, 1990; Walker 2005). However, over time there are small fluctuations in the ratio of ^{14}C to ^{12}C in the atmosphere, fluctuations that have been noted in natural records of the past, such as sequences of tree rings and cave deposits. These records allow fine-tuning, or "calibration", of the raw radiocarbon age, to give a more accurate estimate of the calendar date of the material (Walker, 2005).

Two bulk peat samples from the CAM core were radiocarbon dated using Accelerator mass spectrometry (AMS) at the Poznań Radiocarbon Laboratory, Poland. An AMS separates electrically charged ^{14}C from ^{12}C ions from a sample of peat using an electromagnetic field and these are counted by detectors. The number of counts of ^{14}C from ^{12}C ions from the detectors are used to calculate the ratio of ^{14}C to ^{12}C. The ratios are converted first to 'raw' Carbon 14 dates (which do not take account of natural past variations of the $^{14}C/^{12}C$ ratio) and then to calibrated dates. The results are shown in Table 2.

Table 2 includes the calibrated ages (using CALIB 6.1.1 radiocarbon calibration program and IntCal04 after Reimer *et al.*, 2004; 2009) and error estimates of +/- 2 sigma age ranges. Best estimated ages or calibrated radiocarbon ages (to the nearest five years) are cited in brackets in the text (AD/BC = calendar years). An age-depth curve (Fig.4) was constructed using the Clam software (Blaauw 2010) with the two sample dates plus the present day date of the surface. The curve implies a constant and linear peat accumulation rate which is unlikely. Well dated peat bog records show that the accumulation or sedimentation rate in most archives can vary.

Depth (cm)	Lab no.	Age 14C BP	Calibrated Age
47-48	Poz-50543	1470+30	Cal AD 547-644
170-171	Poz-50544	3970+35	Cal BC 2576-2433

Table 2: ***Radiocarbon dates from CAM***

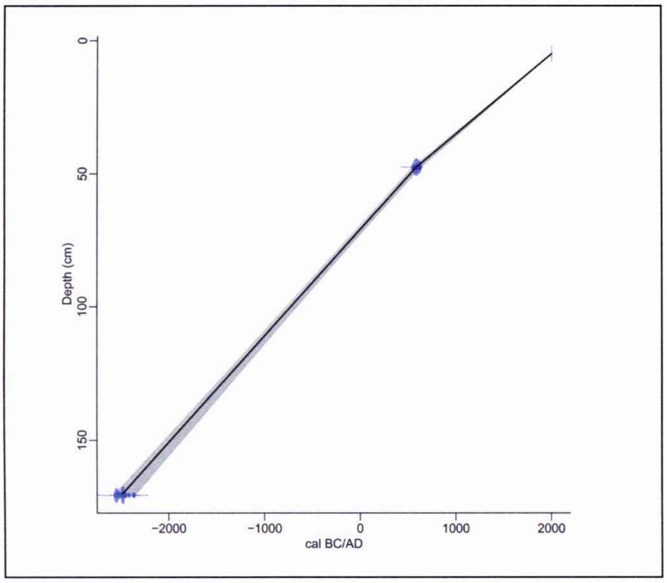

Fig. 4: ***Dating Calibration Curve***

Therefore the estimated dates cited in this paper must be treated with caution and we used a best estimate age for a particular depth (unless otherwise stated) using the age-depth curve.

Microfossils: the pollen and non-pollen palynomorph (NPP) diagrams are shown in Figs. 5a and 5b. Plant nomenclature follows Stace (1997) and Preston *et al.* (2002), and takes into account the problems of categorising plant species on the basis of their pollen morphology (Bennett *et al.*, 1994).

Summary curves for trees, shrubs constituting arboreal pollen (AP), dwarf shrubs and herbaceous non-arboreal pollen (NAP) are shown. NPP terminology follows the type system devised by van Geel (1978) and uses the laboratory code as prefix (HdV), followed by the type number.

The pollen and microscopic charcoal data are expressed as percentages of total land pollen (TLP). NPPs are expressed as percentages of total land pollen plus NPPs. The pollen diagrams were constructed using Tilia and Tilia.graph and zones were delineated using CONISS software (Grimm 1991-1993). Microscopic charcoal pieces were also counted during routine pollen analysis and are expressed as a percentage of total land pollen.

Geochemistry: The profiles for CAM are presented in figures 6 a,b. The pattern for Al, Si, Ti, K, Zr, Mn and Cr are very similar. Notwithstanding the occasional reversal their concentrations increase between 48 and 32 cm. From 32 cm the concentrations rise with three peaks at 24, 16 and 8 cm. Phosphorous concentrations display a similar trend but the dip at 20 cm is more pronounced. The profiles of Cu and Ni show comparable changes: they generally increase from the lowermost sample with reversible dips at 28 and 20 cm. Calcium, Sr, Fe, Pb and Zn have low concentrations at the base of each profile. Their concentrations begin to increase gradually from the lowermost sample, with the rate of increase more pronounced in two stages: from *c.* 30 cm and then from *c.* 20 cm. Only Pb concentrations begin to fall in the uppermost sample. Rubidium and Br concentrations follow a similar pattern: they fall at the base of the profile, then increase between 40 and 18 cm before gradually falling. The pattern for Cl and S is slightly different as their concentrations increase slightly at 40 cm, remain relatively high until 20 cm and then fall.

INTERPRETATION AND DISCUSSION OF THE RESULTS

A blanket peat approximately 2m-deep has accumulated on Camaderry plateau since the Early Bronze Age, around cal BC 2510. However, in order to reconstruct the impact of historical mining at Glendalough and Glendasan, this study focuses only on the uppermost 50 cm of the peat.

Zone 1: This subzone is dated from *c.* cal AD 582 to AD 1010. It is characterised by tree and shrub pollen. *Corylus avellana* (hazel)-type pollen dominates the pollen assemblage with *Quercus* (oak), *Alnus* (alder) and *Betula* (birch) well represented. *Pinus* (pine), *Ulmus* (elm), *Ilex* (holly) and *Salix* (willow) occur as minor components. *Betula* and *Salix* probably occupied the damp margins of lakes, stream and river banks, on wet substrates in valley bottoms and basin mires (Chambers and Price, 1985; Bennett 1986) with the other trees colonising drier and/or fertile soils on floodplains and valley sides (Birks, 1989). *Quercus* and *Alnus* woodland most likely covered the foothills and valleys with *Corylus avellana*, *Ilex* and *Sorbus*-(rowan) type understorey components (Moore and Chater, 1969). However, the mixed woodland is undergoing a phase of gradual decline. *Betula*, *Fraxinus* (ash) and *Ulmus* are most affected.

Coincidently, taxa commonly associated with peat development increase: initially Cyperaceae and then *Calluna* (heather) whilst *Sphagnum* (moss) and *Myrica gale* (bog myrtle) are represented. NPPs associated with *Eriophorum vaginatum* (cottongrass or bog cotton) include *Anthostomella fuegiana* (a fungus; HdV4) and HdV18 whereas *Calluna* is a possible host for HdV10 and HdV20, both of which are commonly recorded. Drier bog surface conditions are also suggested by the presence of *Conciochaeta cf ligniaria* (HdV6) and HdV20, although surface pools exist as spermatophores of Copepoda (HdV28), *Alona rustica* (HdV72A) and HdV140 are present. *Assulina seminulum* and *Amphitrema flavum* (both testate amoebae) are commonly associated with ombrotrophic conditions (van Geel, 1978; Yeloff *et al.*, 2007).

Evidence for human activity is mute. Taxa indicative of pasture, in particular *Plantago lanceolata* (plantain), are consistently recorded but only occur in trace amounts: Ranunculaceae (buttercup family), *Rumex acetosa*-type (sorrel), *Potentilla*-type (cinquefoils) and Lactuceae (dandelion). Very low percentages of disturbed ground indicators *Anthemis* type (chamomile), Chenopodiaceae (goosefoot) and *Urtica* (nettle) are also recorded. The changes identified in the pollen record could relate to land use at lower altitudes, with pollen being transported by wind on to the upland plateau (Price and Moore, 1984).

Subzone 2a: This subzone is dated from *c.* cal AD 1010 to

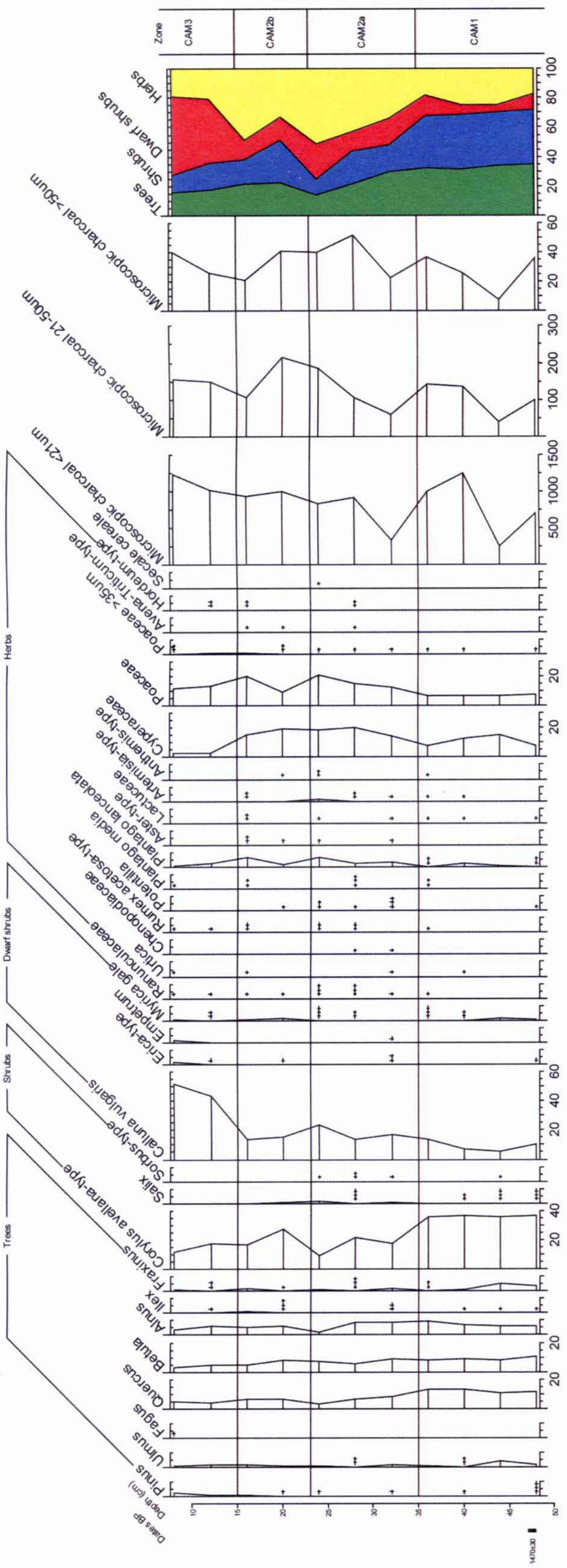

Fig. 5a: Pollen and Charcoal Percentages with summary of main vegetation groups by sample depth

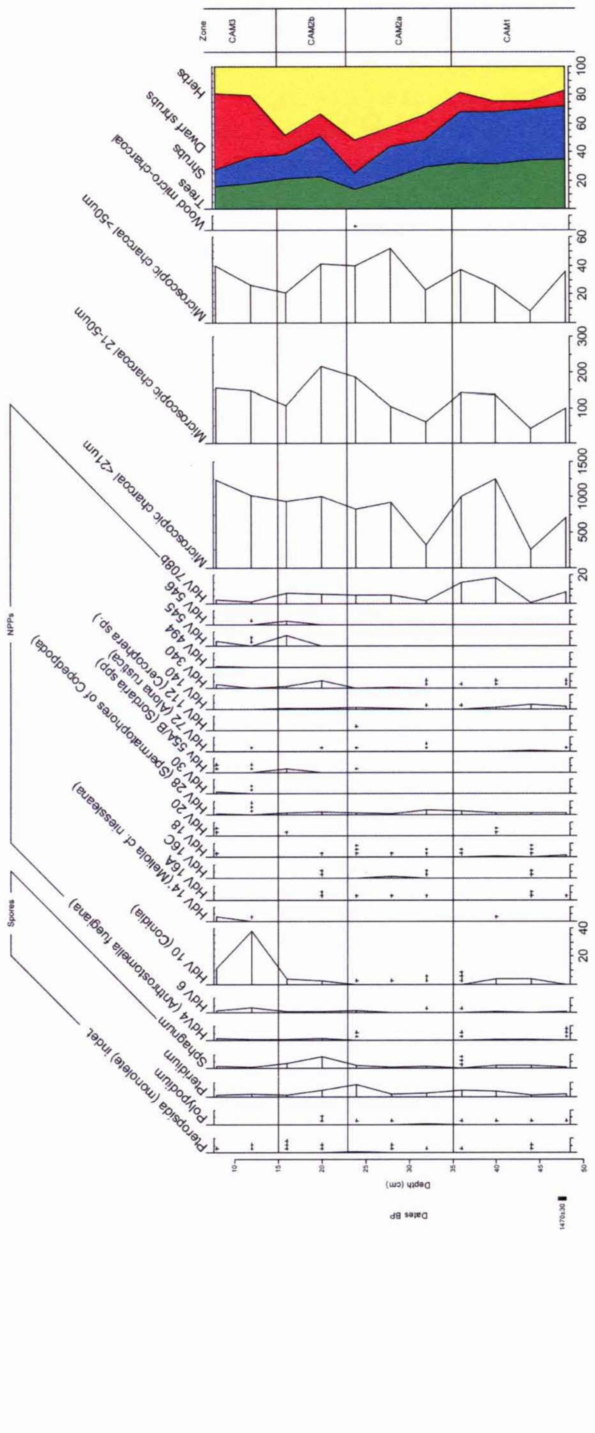

Fig. 5b: NPP Percentages with summary of main vegetation groups by sample depth

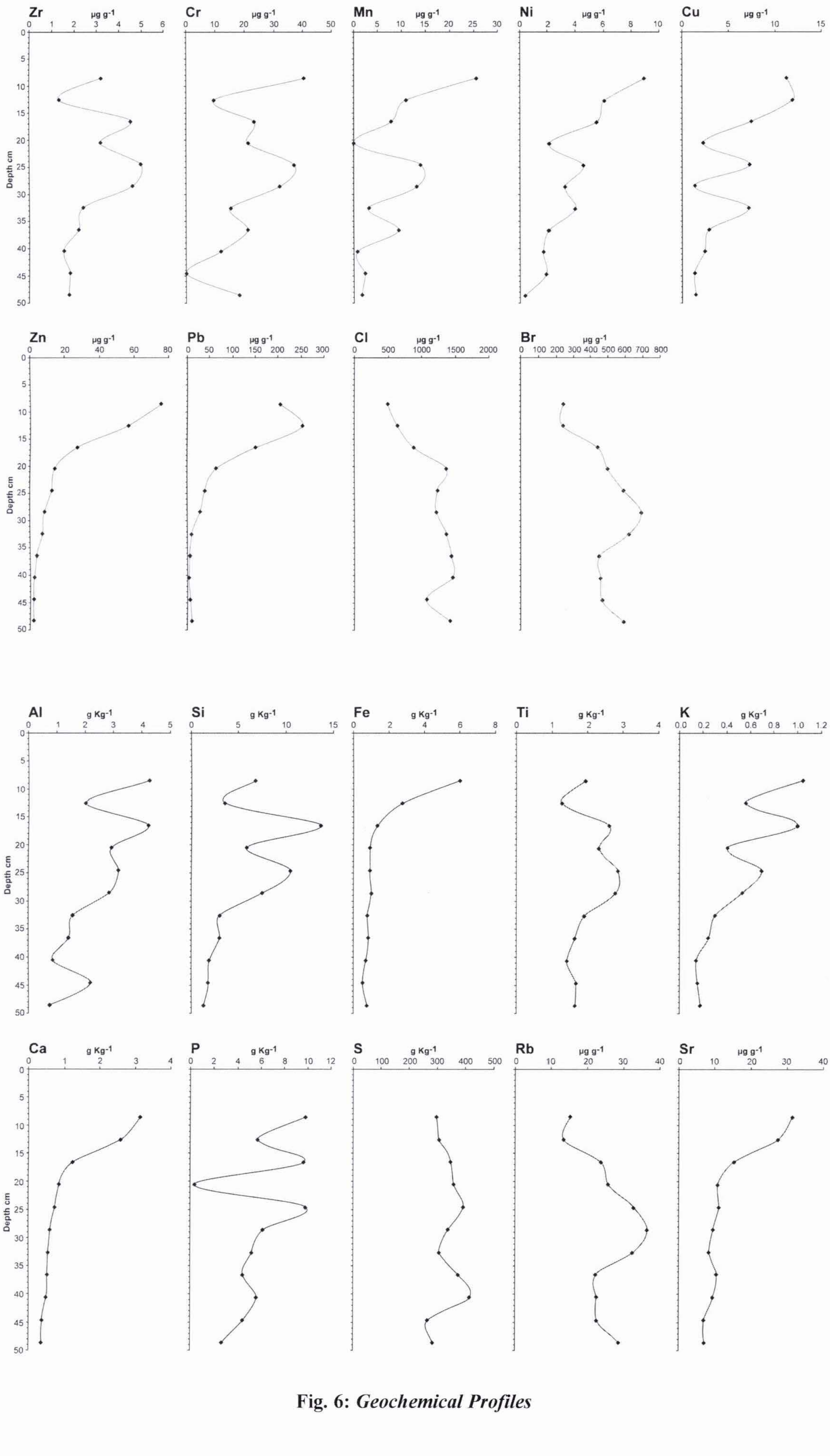

Fig. 6: *Geochemical Profiles*

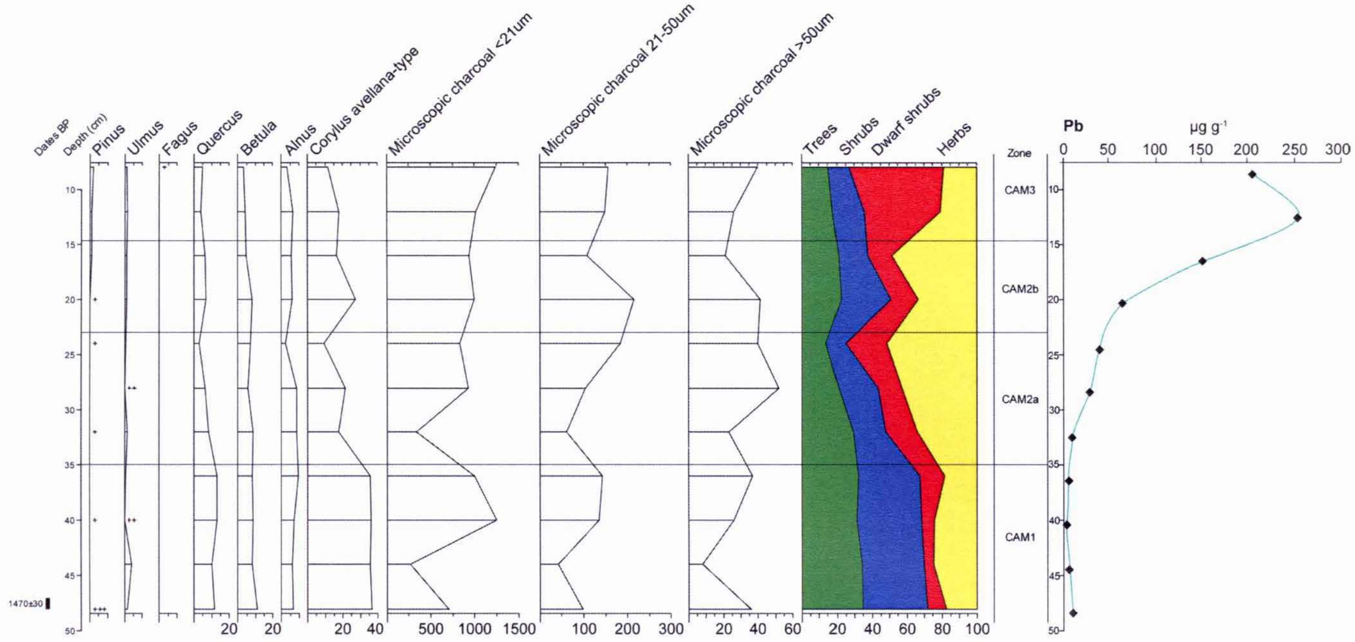

Fig. 7: *Comparison of main Pollen taxa, vegetation groups and lead with depth*

also diminished.

The sizeable increase in *Calluna* pollen suggests that the extent of the blanket peat has increased over the last 350 years and/or that the blanket peat surface become drier. *Calluna*, *Erica*-type and *Empetrum* percentages increase as Cyperaceae and *Sphagnum* decline. Drier conditions are also supported by the increase in HdV10 (Yeloff *et al.*, 2007). NPPs suggestive of open pools also fade whilst fungi associated with bog plants are represented, including *Anthostomella fuegiana*, HdV4; HdV14 and HdV20.

Geochemistry

Whilst it is plausible that mining in County Wicklow may have first commenced during the Bronze Age, evidence for such activities has yet to be discovered. The first documented evidence for lead mining at Glendasan and Glendalough is in the early nineteenth century (Schwartz and Critchley 2012) with mining in the neighbouring valley of Glenmalure from the eighteenth century and the distinct possibility of unrecorded earlier mining on Camaderry Mountain (Glens Of Lead). The geochemical data for CAM are presented in Fig. 6 and the chronology from the peat core covers this time period (for ease of comparison Fig. 7 shows the lead profile against the main tree taxa and microscopic charcoal counts). Higher concentrations of Pb occur from 32 cm (*c*. AD 1078), and then increase more dramatically at 21 cm (*c*. AD 1480) to peak at 12 cm (c. AD 1780) and drops slightly at 8cm (c. AD 1880). The early record of Pb pollution predates the first reference to local mining and might be indicative of lead mining extending back into the early medieval period in the area.

Dolan (2009) suggests that the bullaun stones at Glendalough might be related to early mineral processing, citing the fact that examples excavated elsewhere in Ireland are proven to have been associated with Iron Age and early medieval metal working sites. It has been suggested that the unusually high concentration of bullaun stones (which contain hemispherical hollows up to about 10 cms deep) recorded by Price (1959) at Glendalough might not have had a ritualistic purpose. The Record of Monuments and Places records 23 bullaun stones in the Glendalough area, most of which are not actually within the monastic site, but clustered further to the east in close proximity to the old St Kevin's Way, one of the main medieval routes to the monastic city. However, no geochemical analyses of soils near the bullaun stones have been undertaken and Collins (2013) claims that they were more likely to have been used to grind gorse for use as an animal fodder, while others have suggested they were used, as across the Americas, to grind acorn into meal (see Bullaun Stones on Boards.ie).

Copper and zinc also have elevated concentrations and this most likely reflects mining and metallurgical activities. Zinc concentrations actually begin to rise just before Pb and may be due to post depositional mobility (Mighall *et al* 2002b). However, the pattern is virtually identical to lead which suggests that the zinc pollution signal is a consequence of lead mining although zinc was also targeted by miners in the mid 1900s at Glendasan. Copper also increases along with Pb and Zn but suffers from reversals at 20-21cm (*c*. AD 1480) and 28-29 cm (*c*. AD 1210) respectively. It is possible that these declines reflect a reduction in amount of copper ores mined. The pattern of nickel concentrations is very similar to copper. It is unlikely nickel was deliberately targeted: its pollution signal is most likely caused by its association in mineralised veins with targeted metals.

The relatively coarse resolution of the geochemical record prevents a more direct comparison with the changing fortunes of Wicklow lead mining industry during the nineteenth and early twentieth century's. The peak at 12cm (c. AD 1780) corresponds to the known phase of modern mining in the late eighteenth century but predates the peak lead ore production in the middle of the nineteenth century. The apparent offset between the lead peak and the mining peak is probably due to the imprecise dating of the core sample (due to varying rates of peat accumulation) between the known surface date and the two radiocarbon dates. A more detailed record could be achieved by improving the chronological record of the peat core during the last 200 years by Pb^{210} dating and analyzing more samples. Extending the sampling down throughout the core might reveal earlier evidence for mining, especially during the late Iron Age (corresponding with the Roman period) and possibly the Bronze Age. Pollution signals for both periods have been recorded in bogs elsewhere in Britain including in mid-central Wales (e.g. Cwmystwyth; Borth Bog; Mighall *et al*., 2002a & b, 2009) and recently at Annaholty Bog, near Limerick (Kuttner, 2013). Analysis of lead isotopes ($^{206}Pb/^{207}Pb$ and $^{208}Pb/^{206}Pb$ ratios) for the peat core and comparison with lead isotopes from the mineral veins (and reference sites in Europe) would help to strengthen the relationship between the lead record in the peat core and the mining at Glendalough.

Concentrations of lithogenic elements, both biophylic (K, Ca, Sr, Rb) and non-biophylic (Al, Ti, Si, Zr), all increase in two stages. They increase gradually from relatively low concentrations at 40 cm (*c*. AD 810) and then more dramatically from 33 cm (*c*. AD 1078). The latter rise coincides with the increase in metal concentrations associated with mining and woodland clearance (as recorded in the pollen diagram). Mining activities would have exploited local woodlands for timber which could lead to woodland clearance although evidence from other metallurgical sites suggests that miners/metalworkers would manage woodlands to protect their timber supply (e.g. Crew and Mighall, 2013). Alternatively, woodland could have been cleared to create agricultural land. This would lead to soil erosion which is reflected by an increase in the deposition of lithogenic elements on the peat bog surface (e.g. Holzer and Holzer, 1998; Martínez Cortizas *et al*. 2005). Therefore it is likely the origin of the heavy metals recorded in the Camaderry bog is derived from two principal sources: directly from dust produced by mining and/or from increased soil erosion as a result of woodland clearance.

The increase in elements such as Ca, Sr, Fe and K at the bog surface is likely to be the result of biological recycling and uptake by living plants (Martínez Cortizas *et al*., 2005). Other elements decrease (e.g. Si, Ti, Rb and Zr). The decline of these lithogenic elements suggests the amount of dust deposition from soil erosion has declined (Martínez Cortizas *et al*., 2005) as the impact of human activities (both mining and agriculture) recedes.

Although the pattern of lead and zinc in the peat core strongly hints at pre-eighteenth mining at Glendalough, other sources could also be responsible. Indeed, the date range concurs with records of active lead mining at Silvermines in County Tipperary (Cowman 1988). This pattern is also consistent with the development and expansion of lead mining across Europe (Claughton and Rondelez, this journal), including extensive workings in the British Isles. This activity generated significant pollution that has been recorded in peat bogs across NW Europe (e.g. Martínez Cortizas *et al*., 2002; De Vleeschouwer *et al*., 2010) including England (Le Roux *et al*., 2004), Scotland (e.g. Farmer *et al*., 1997, Cloy *et al*., 2005) and Wales (e.g. Mighall *et al*., 2002a,b; 2009).

Moreover, evidence has been presented which demonstrates that lead dust can travel over large distances. For example Shotyk *et al* (1998) have shown that lead found in a bog in Switzerland was derived from mining activities in Spain and Rosman *et al*. (1997) have analysed ice cores from Greenland which have lead signals from Roman mining, also in Spain. However, in both of these examples the lead concentrations were low (approximately 20 $\mu g\ g^{-1}$ or less) when compared to a maximum of over 200 $\mu g\ g^{-1}$ in the Glendalough core. Perhaps these lower lead values are due to dissipation caused by the trans-global airborne dissemination of lead bearing dust particles. Therefore, it would be reasonable to assume that the high concentrations of lead in the Glendalough core were derived locally rather than airborne from mining a considerable distance away. By way of comparison, analysis of a peat core sample from Lindow bog near Manchester in England, which is about 30 km from the Derbyshire lead mining field, shows lead values in the nineteenth century of over 200 $\mu g\ g^{-1}$ (Le Roux *et al*. 2004). The high lead values in the nineteenth century peat stratum from Lindow and the proximity to mining reinforce the hypothesis that the high lead values in the Camaderry peat core are the result of mining in the vicinity.

CONCLUSIONS

In conclusion, the results of the core sampling are exciting as they indicate possible mining in the Glendalough area from the eleventh century onwards and in particular a rapid growth from the fifteenth century. In light of this, perhaps we need to reconsider if the reason for the location of the Monastic City of Glendalough has less to do with religious asceticism and was instead related to the nearby presence of silver bearing lead ores? Monasteries were not just centres of spiritualism but an important part of the economy in the middle ages. This paper also highlights the need for more research, such as sampling adjacent bogs to investigate the spatial distribution of lead anomalies, analysis of the lower sections of the peat to see if there are Roman or other metal anomalies, analyses of lead isotopes to trace sources, and more detailed radiocarbon dating.

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