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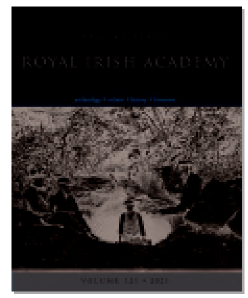

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Palynological investigation of a later Bronze Age copper mine at Derrycarhoon in south-west Ireland

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Abstract

This paper presents the results of a recent palynological analysis at a prehistoric mine in the Mizen Peninsula of West Cork. Archaeological survey and excavation confirm Derrycarhoon is the first copper mine in Ireland dated to the later Bronze Age, *c.*1400–1000 BC. The production there represents the end of a mining tradition in the south-west region that began a millennium or so earlier at Ross Island, Co. Kerry. The palynological study at Derrycarhoon examines the contemporary environment of the early mine, to understand its effect on local vegetation during the later second millennium BC. This environmental impact was reduced by the small scale of ore extraction over several centuries, and by a mining technology that did not significantly impact local woodland at a location where contamination from surface ore-processing was both short-lived and localised. The results add to information on the variability of environmental impacts caused by mining and metal production in prehistoric Europe. Finally, this study contributes to a wider understanding of vegetation history and anthropogenic influences during the Holocene in the West Cork region.

Ancient mining and the environment

Public concern with mining today often centres on the negative consequences for the natural environment, as well as health and quality of life implications for local communities. This includes the physical alteration of landscape, atmospheric and groundwater pollution, and resulting effects on vegetation and the food chain. There were also various environmental impacts around the extraction of metal in prehistory, the scale of which largely depended on the intensity and duration of mining at different locations. This ranged from short-lived operations, often seasonal, producing small amounts of metal for local needs, to more sustained activity undertaken by established mining communities that supplied significant amounts of metal over a wide area through organised trade.

The environmental impact of most prehistoric copper mines was confined to the extraction site and its immediate surroundings. There are examples where the scale of operations had greater consequences for the local or wider

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environment. These include the Bronze Age mines of the Austrian Alps, with an estimated output of 20,000 tonnes or more of raw copper from the main Mitterberg deposit, and perhaps 50,000 tonnes from the region as a whole during the second millennium BC (Pittioni 1951; Stöllner 2019). Pearce (2009) has estimated a combined extraction of 4500 tonnes of copper ore in the mines of Monte Loreto and Libiola in eastern Liguria, yielding as much as 788 tonnes of raw copper during the fourth and third millennia BC. Another example is the Copper Age mine at Ai Bunar in Bulgaria, estimated to have produced 2000–3000 tonnes of copper ore, yielding up to 500 tonnes of metal (Chernykh 1998a). On a much larger scale is the Kargaly mining district in the South Urals, where 2–5 million tonnes of copper ore were mined during the Bronze Age (*c*.3000–1400 BC), producing as much as 150,000 tonnes of metal (Chernykh 1998b).

While the physical size of these ancient mine workings provides some indication of gross output, this must be considered against the temporal scale of production. The environmental impact of a small mine working over many centuries to meet local needs was different to that of larger operations worked intensively over short or long periods. An example is the Great Orme in Wales, which may have produced at least 175 tonnes of copper during the Bronze Age (Lewis 1998; Williams 2019). That impressive output must be placed against the extended working of the mine *c*.1700–1300 BC, and possibly longer, with an annual output of perhaps 200kg of metal. There are also many examples of smaller-scale mining of shorter duration. These include the Mount Gabriel-type copper mining of south-west Ireland, dated to the Early/Middle Bronze Age (*c*.1800–1400 BC). The production of metal on Mount Gabriel itself *c*.1700–1400 BC is estimated at 1.5–30 tonnes, with output probably at the lower end, enough to produce 40–50 bronze axeheads a year (O'Brien 1994, Table 12). The slow release of metal from small-scale mines contrasts with the intensive production mentioned above, with different consequences for the environment.

Palaeoecological approaches

The environmental impact of ancient mining can be assessed using palaeoecological data collected from the mine sites or from natural environments in the vicinity. Peat bogs can contain a range of biological and geochemical proxies (pollen, microscopic charcoal and heavy metals) connected to early mining and metallurgy. Pollen records provide an insight into how mining and smelting interferes with local woodland, while a rise in heavy metal concentrations in bogs, lakes and glaciers, can be an indicator of both activities. Many studies confirm the value of a multi-proxy approach that combines palynological (pollen and micro charcoal) with geochemical data to examine both the environmental setting of a mine and the impact on the natural environment.

In many cases the most severe impact on the environment was connected to the supply of wood. The intensive use of fire-setting to extract rock consumed enormous amounts of fuel. Wood was also required to make equipment of various kinds, as well as props for roof support, and domestic use in mining camps. The smelting of copper ore using large amounts of charcoal was another draw on local woodland. Such demands impacted on tree growth in the immediate vicinity of the mine, and possibly farther away. Some mines were located in areas of naturally abundant woodland, while others, particularly those at higher altitudes, had only limited tree growth in the vicinity.

For mines where there was intensive fire-setting the supply of wood required careful management. Experimental studies on Mount Gabriel suggest that a single 10m deep mine involved 100–200 fire-setting cycles, consuming as much as 138–509 tonnes of roundwood fuel. The 30 or so workings identified on that mountain would have used 3900–14,500 tonnes of roundwood fuel to extract an estimated 4000 tonnes of rock (O'Brien 1994, Table 10). Perhaps surprisingly, pollen data for Mount Gabriel indicates a pattern of sustained, but limited, woodland clearances during the earlier part of the Bronze Age (Mighall *et al*. 2000). The mines appear to have had little impact on local woodland, with species such as oak and hazel actually increasing in abundance during the mining period. This can be explained by the small-scale and sporadic nature of this mining, and the selective manner in which branch wood fuel was gathered. While the gross consumption of fuel was enormous, this mining was conducted on a seasonal basis across three centuries or so. That reduced the immediate impact of wood collection on the local environment, allowing time for regeneration of local woodland. Analysis of waterlogged wood from the mines indicates that the miners avoided mature trunk wood as fire-setting fuel, opting for selective felling of roundwood branches and adventitious coppice from younger growth (O'Brien 1994, 265–80). There may have been occasional clear-felling of mature trees, but generally the miners extracted branch wood from trees that regenerated over a number of years.

Palynological studies were also undertaken at a Bronze Age mine on Copa Hill, Cwmystwyth, in mid-Wales (Mighall and Chambers 1993; Mighall *et al.* 2012). Analysis of peat cores taken 500m from the mine record a series of short-lived declines in tree pollen during the mining period, mainly oak and hazel, which correlate with higher copper concentrations in the bog. This indicates small-scale, non-permanent phases of woodland disturbance confined to the general mine area. The Mount Gabriel and Copa Hill results indicate a series of small, short-lived declines in tree pollen probably connected to mining, where local woodland was not permanently affected by this activity. There are similar findings from palynological analysis conducted near Bronze Age mining sites in Steiermark, eastern Austria (Marshall, O'Hara and Ottaway 1999). Research at Kelchalm in Kitzbühel (Viehweider and Oeggl 2012), and in the Falkenstein mining district of North Tyrol (Breitenlechner *et al.* 2010), identified changes in vegetation linked to Bronze Age mining. Again, this did not involve the wholesale destruction of tree cover, but rather local variations in woodland density and species representation. Similar results were obtained for pollen studies at the

Iron Age copper mine of Campolungo, in the Lombard Alps of northern Italy (Mighall *et al*. 2003). None of these prehistoric mines can be linked to permanent reduction in tree cover or to any long-term impact on the environment.

The use of charcoal as smelting fuel was another demand on woodland resources, one that is often associated with iron production in historic times. As with mining, that depended very much on the scale and duration of this activity. While copper smelting at small mines such as Mount Gabriel had a limited impact on local woodland, it has been suggested the forests of Cyprus were cut down sixteen times to meet the fuel needs of Bronze Age copper production (Constantinou 1982). That indicates a considerable regenerative ability or else careful woodland management to maintain the fuel resource. Even greater are fuel demands arising from the smelting of several million tons of copper ore at Kargaly during the Bronze Age to produce an estimated 150,000 tonnes of metal. Rovira (1999) estimates this required approximately 75 million tonnes of wood, which Chernykh (1998a) suggests led to the deforestation of up to 3000 square kilometres in the region.

As well as deforestation, mining and smelting can also result in atmospheric pollution, leading to elevated levels of heavy metals in depositional environments. Studies in France, Italy and Spain, have identified heavy metal concentrations in upland mires and lakes, and river estuaries, believed to be airborne pollutants from early metal production (Monna *et al*. 2004; Le Blanc 2005; Guyard *et al*. 2007; Bailly-Maitre and Gonon 2008; Carozza *et al.* 2010; Braithwaite *et al.* 2012). Evidence of atmospheric pollution connected to Bronze Age copper mining was found at Cwmystwyth and Mount Gabriel (Mighall 2003; Mighall *et al.* 2012). Geochemical analysis of peat profiles at both locations identified enhanced metal concentrations that resulted from either smelting emissions or dust blowing from exposed mine spoil. The extent of that pollution is unclear, but was probably restricted to the vicinity of those mines.

The interpretation of geochemical and air-borne charcoal data is complex and is best considered in combination with pollen and other evidence. Much depends on the duration and intensity of the mining activity, and whether smelting was undertaken in the vicinity. Higher concentrations of charcoal should correlate with changes in arboreal pollen and pollution signals caused by early mining, particularly where fire-setting was employed. Smelting activity provides another source of wind-borne charcoal. This phenomenon has been studied at both Mount Gabriel and Cwmystwyth, where it has not proved to be a reliable indicator of mine fire-setting or smelting (Mighall *et al.* 2012*,* 127). The problem partly lies in distinguishing charcoal produced by mining and metal production from contemporary agriculture and settlement in the same locality. No such data is available at the present time for Derrycarhoon, where soil and stream geochemical anomalies outside of the mine site probably relate to geological background values for copper and other metals (see Keele 1969).

Miners and farmers

There is much evidence across Europe that farming systems supported prehistoric copper mining (O'Brien 2015, 263–9). The faunal record from excavated mines provides an insight into the supply of food from local farms (e.g. van Wijngaarden-Bakker in O'Brien 2004; Schibler *et al*. 2011; Trebsche 2012). Mining and farming are labour intensive, and so required careful organisation and collaborative effort at a community level to be successful. While larger permanent mines may have had a permanent workforce, many smaller ventures were probably worked on a seasonal basis by miner-farmers, overseen by a smaller number of specialists. In some cases mining was a late-autumn/winter activity, which may have commenced each year following the harvest. However, the evidence for seasonality is often equivocal, and so it is not possible to state that mining was not carried out at other times of the year. There may have been close connections between the initiation of copper mining and farming in upland environments. For example, Maggi and Pearce (2010) suggest that the emergence of copper mining in Liguria during the fourth millennium BC coincided with an increased investment in animal husbandry and the exploitation of new land by mobile pastoralism. It is often suggested that a search for valuable resources such as copper and salt, together with transhumant farming, was central to the settlement of the Alps by Bronze Age people.

A recent study in south-west Ireland examined the settlement context of Bronze Age copper mining in an upland landscape (O'Brien 2007; 2009). The investigation focused on the upland valleys of the Beara peninsula, where early field systems, habitation sites and ritual monuments are preserved under blanket bog. A Mount Gabriel-type copper mine in one of these locations, the Barrees valley, is dated 1700–1500 BC. There is evidence of contemporary settlement in the valley below this mine, represented by burnt mound cooking sites and a standing stone pair of ritual/funerary significance. The pollen record indicates sustained human activity in the valley from the Middle Bronze Age onwards, mostly connected to pastoral farming with an arable component (Overland and O'Connell 2008). While no direct link can be established, that farming is likely to have supported the mine overlooking the valley. The results emphasise the difficulty of linking small-scale mining events, with a duration of a few decades, to a continuum of human settlement and farming practice in the same landscape over thousands of years. Whereas a mine is located on a geological mineral occurrence, the associated settlements may have been close or some distance away, as determined by local environment and socio-economic factors. These questions will now be considered in relation to the environmental signal of a Bronze Age copper mine in the West Cork region.

Derrycarhoon mine

The south-west region of Cork and Kerry was the most important source of copper in Ireland during the Chalcolithic and Bronze Age. Copper mining began *c.*2400 BC at Ross Island in Killarney, Co. Kerry, and continued there to *c.*1800 BC (O'Brien 2004). The abandonment of that mine coincided with the commencement of copper extraction on Mount Gabriel and at least ten other locations in the peninsulas of Cork and Kerry (Fig. 1; O'Brien 1994; 2003). This is an area of sedimentary rocks of late Devonian age, where beds of green sandstone contain low-grade disseminations of oxidised copper minerals. Those 'copper-beds' were extracted in surface drift mines of the Mount Gabriel type using fire-setting and stone hammers. That mining largely ceased across the region *c.*1400 BC, but did continue in a different form at one location.

Derrycarhoon copper mine is located 6km north of Ballydehob village in the Mizen Peninsula of Co. Cork (Fig. 1). Until recent years, this small copper mine was visible in a forest clearing (Pl. I) at an elevation of 155m on the southern slopes of a ridge that extends east from Mount Kid (298m OD). That conifer forest was clear-felled in 2014 (Pl. II), but is now subject to further

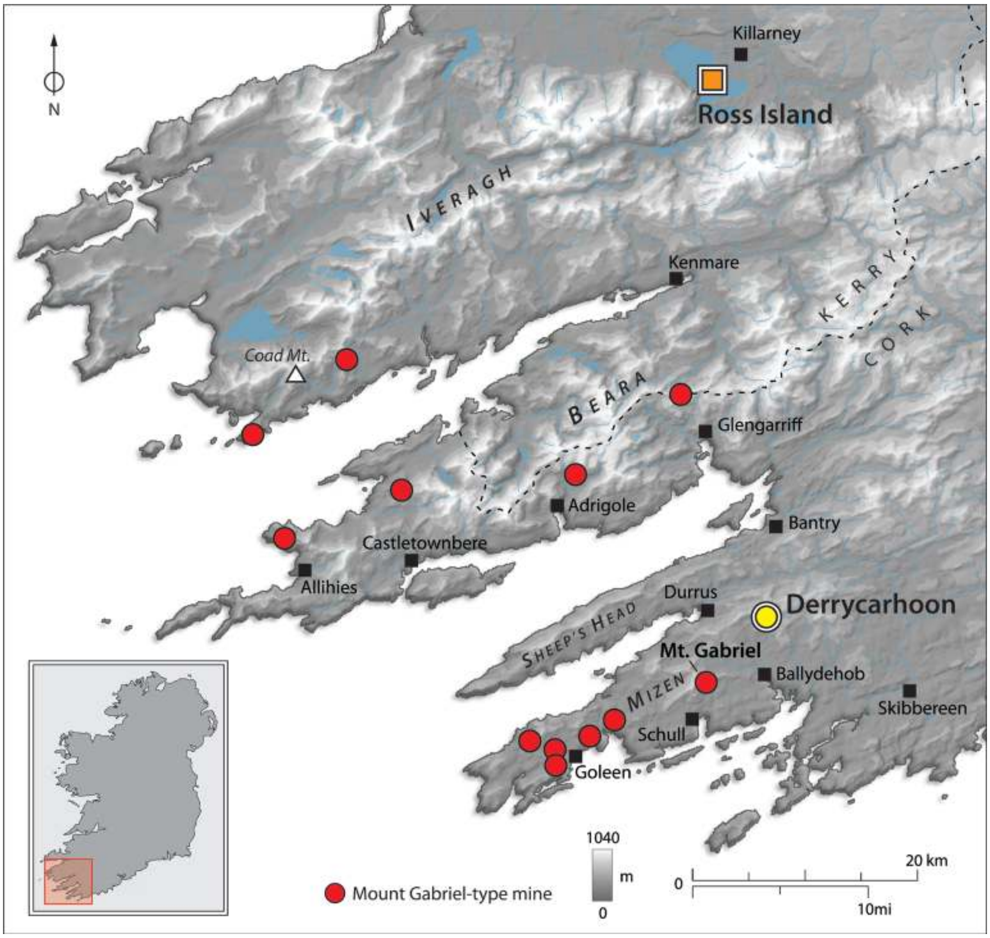

Fig. 1—Prehistoric copper mines in south-west Ireland, highlighting location of Derrycarhoon mine.

Pl. I—Central mine area in forest clearing at Derrycarhoon (2013).

Pl. II—Derrycarhoon copper mine after clear-felling of forestry in 2014 (source: Nick Hogan).

planting. The mine re-opened in 1846 for a short period, leading to the discovery of old workings and mining tools, attributed at that time to the 'Danes' (discussed in O'Brien 1989). The finds comprised stone hammers and wooden equipment, including a notched tree trunk ladder, and a curved tube of yew wood, radiocarbon dated AD 1044–1284 (Briggs 1984), now interpreted as a musical instrument of later medieval date.

Recent archaeological survey at Derrycarhoon identified surface mine workings and deposits of rock spoil (O'Brien 2013; O'Brien 2019; O'Brien and Hogan 2012). These include two vertical mine shafts that were sunk in the nineteenth century and are now infilled. The underground workings of that period are inaccessible. There is evidence of earlier copper mining in the form of six parallel trenches (M1–6), up to 30m in length and 2–3m in width, which cross the site in a north-east/south-west direction (Fig. 2; Pl. III). One of these, Mine 5, is a row of closely spaced vertical pits, now mostly infilled by

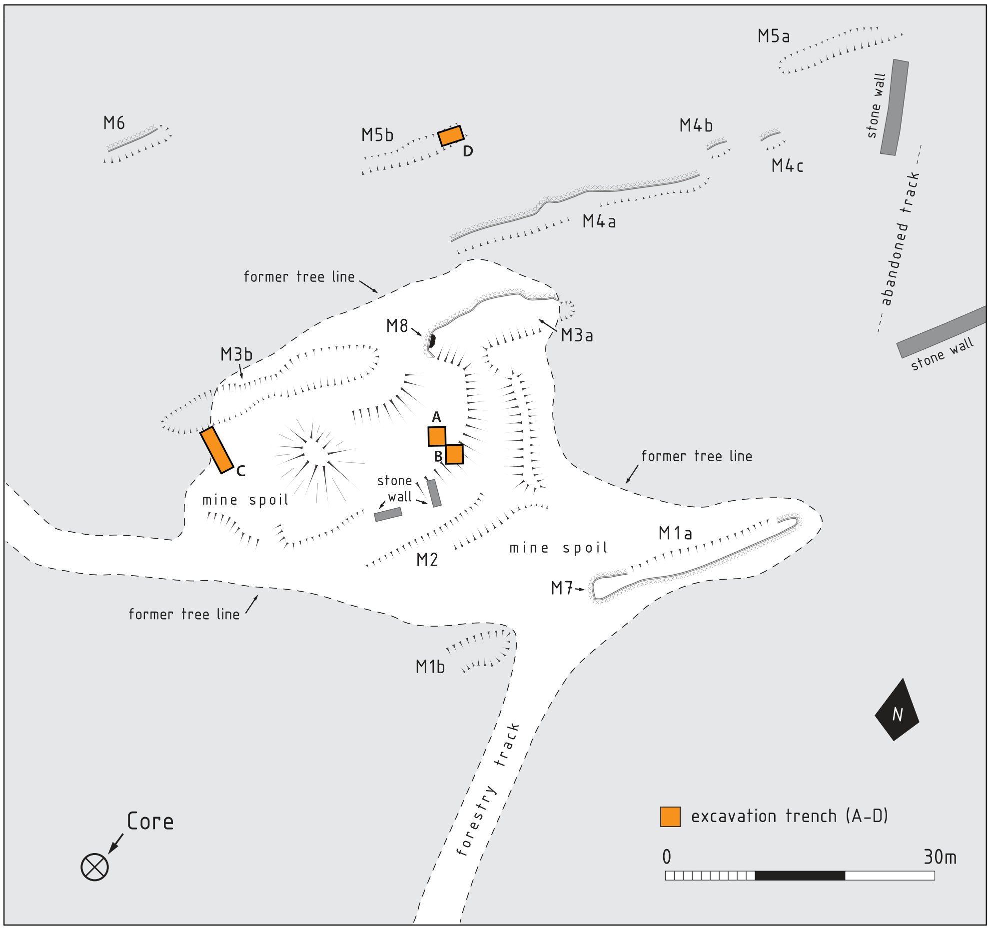

Fig. 2—Plan of Derrycarhoon mine, showing Bronze Age trench mines (M1–6), archaeological excavation trenches (A–D), and location of pollen core.

Pl. III—Bronze Age trench mine, Derrycarhoon.

peat. An exposed length on the western side (Mine 5b) measures 11.5m long by 2.15m wide. A 3.35m long section of this trench was excavated in summer 2011 (cutting D). This exposed a near-vertical, rock-cut pit (Mine 5b-1) measuring 2.75m long by 1m wide by 4m deep (Pl. IV). The shape and size of this mine was determined by its stratabound position along a steeply dipping bed of grey sandstone with copper minerals.

Excavation in 2011 revealed that the upper part of this pit was filled to a depth of 2.4m by compact peat (Layer 2; Fig. 3). This peat accumulated as dead grassy vegetation settled in the open flooded mine over a long period. This is confirmed by a radiocarbon date of 516–206 BC for a sample of peat taken at a depth of 1.5m in the working. This peat overlay a deposit of stony sediment (Layer 3), which comprised slabs of sandstone up to 0.6m in size and smaller rock fragments. A large number of broken stone hammers were recovered from this layer, as well as fragments of waterlogged wood. The latter included some lengths of roundwood with chop marks, one of which is radiocarbon dated to 1114–921 BC.

Further excavation exposed a deposit of finely broken stone (Layer 4) at the base of the mine. The deposit contained broken stone hammers, as well as occasional fragments of roundwood. Some items of worked wood were found, including part of a stone hammer handle, a wedge and two large branches used as crude ladders. Part of a red deer antler pick was recovered, the first such find from an early copper mine in Ireland. A radiocarbon date of 1386–1132 BC for

Pl. IV—Bronze age mine pit (5b-1) after 2011 excavation, Derrycarhoon.

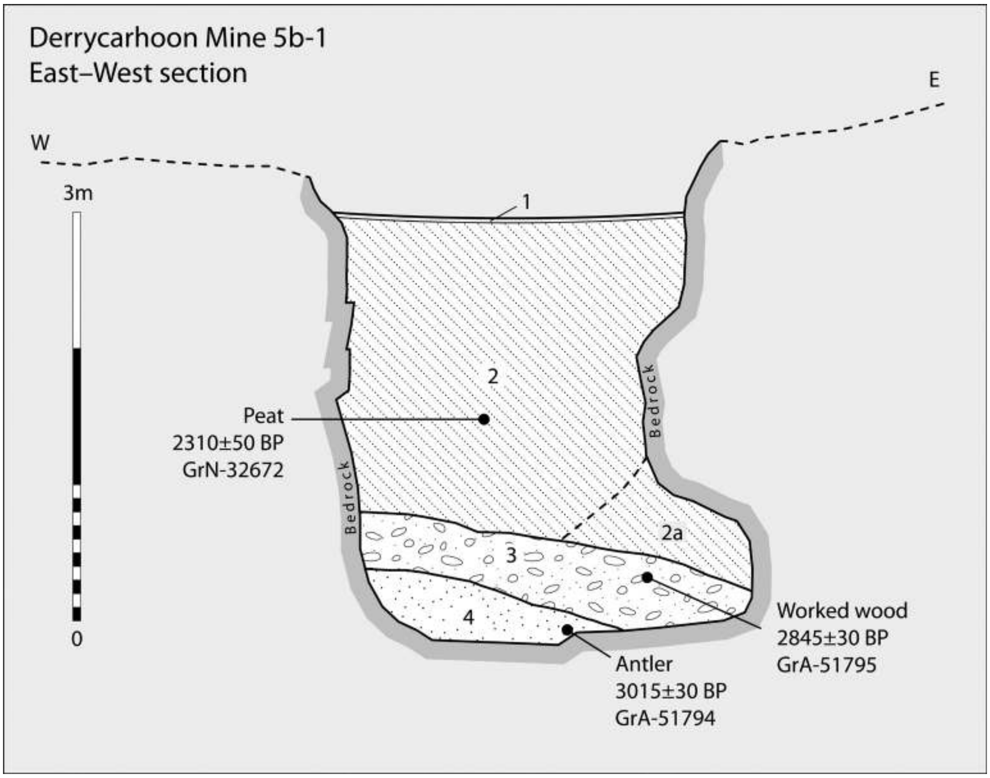

Fig. 3—Section of excavated mine (5b-1) showing peat infill, Derrycarhoon.

this antler, together with a result of 1378–1119 BC for a hammerstone withy, indicate the working period of the mine pit.

This Bronze Age mining produced surface deposits of broken rock spoil in the central mine area, which were added to by later mining. Test-pit excavation in 2010 (cuttings A and B; Fig. 2) uncovered a thin deposit of early spoil containing broken stone hammers and fragments of waterlogged wood. A fragment of rowan roundwood with chop marks is radiocarbon dated 1370–1021 BC, while a piece of young oak is dated 1369–1059 BC, and a twisted hazel withy 1410–1114 BC. These results indicate this spoil came from a mine contemporary with the Mine 5b-1 working, including the adjacent Mine 3 trench that was emptied in the 1846 operations.

To summarise, radiocarbon results from Derrycarhoon date this copper mine to the Middle-to-Late Bronze Age transition, *c.*1400–1000 BC (Fig. 4). The peat date from Mine 5b-1 (Fig. 3) indicates the mine was probably abandoned early in the first millennium BC. The mining at Derrycarhoon is a development from the earlier Mount Gabriel-type extraction of similar ‘copper-bed’ mineralisation in the region. Unlike those mines there is no evidence for the use of fire-setting at Derrycarhoon. The wallrock profile in Mine 5b-1 does not have the smooth concavities typically produced by fire-setting, nor were fuel residues in the form of charcoal or burnt roundwood found in that working or in surface spoil. Fire-setting is not particularly suited to the sinking of vertical workings, such as the Derrycarhoon mine trenches. The copper-beds there are steeply dipping with a penetrative rock cleavage on a near-vertical axis. This allowed the miners to drive down into the lamination of the hard siliceous rock using stone hammers, wooden wedges and antler picks to prise rock along that natural lamination. Apart from those tools, and the likely use of monoxylous ladders, there is no evidence that wood was used extensively in these mines. No trace of smelting

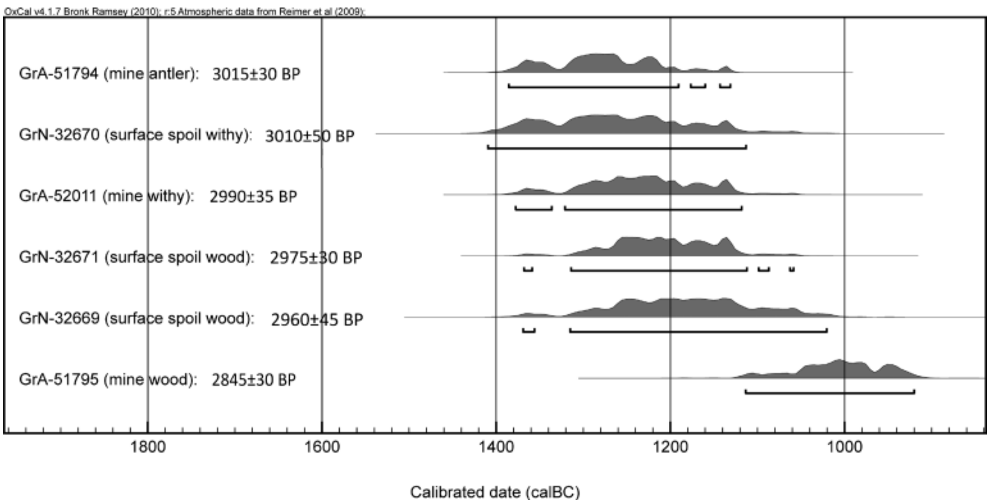

Fig. 4—Calibration of radiocarbon dates from Bronze Age mine at Derrycarhoon.

was found, though that is likely to reflect the low visibility of such evidence at a mine site that has been disturbed considerably in the modern era.

Peat associations

Since their discovery in 1846, there are several published references to the depth of peat in the early copper mines at Derrycarhoon. Correspondence at that time between local historian, Thomas Swanton, and the Cork antiquarian, John Windele, include this comment by the mine captain at that time, Charles Thomas:

> They were found filled at bottom with rubbish, and at the top with bog-stuff, the upper part of which was solid bog apparently of natural formation. The bog stuff extended in some places 14 feet deep but it was not all solid, part of it was missed with rubbish [mine spoil] (Swanton/Windele letter, 9 May 1846; RIA ms 12L10, fol. 103–105; cited in 'Ancient Mining in Ireland', *Mining Journal* 1847, 70).

The implications for dating were apparent to the geologist Henry Kinahen, who observed (with some prescience), 'this working must have been very ancient, as when found all traces of the surface entrance were smothered up by a growth of peat, over fourteen feet thick; this ought to represent a period of, at the least, 3000 years or more' (Kinahen 1886, 202).

This was disputed by Briggs (1984), who argued the peat in those mines was a deliberately backfilled deposit. That view is not supported by contemporary records of 'solid bog apparently of natural formation', nor by recent excavation and coring of the early mine workings (see O'Brien 2019, 127–31).

In addition to mine infill, there are historical records of peat associations on the spoil and periphery of the mine area. The Swanton letter of 1846 referred to 'a stratum of whitish slime (such as runs off in the washing of copper) lying between two strata of bog, the upper of which is three and a half feet thick. The bog in which this appears lies a few yards lower down the hill than the mouths of the mines'. Swanton regarded this 'as a help to arrive at some conclusion as to the date of these works' (O'Brien 2019, 127–31). Another account records 'these excavations [trench mines] in time filled up with peat from the adjacent mountains, in which was found a quantity of pure copper precipitated probably by the action of the acid and iron in the peat and copper in solution exuding from the ore' (Anglo-Celt 1849). William Thomas, a brother of the mine captain, observed that 'in one of the Dane's Works at Derrycarhoon, which in the course of ages had become full of peat…I have seen the fibres of the peat completely precipitated or formed into pure copper, like so many beautiful hairs or fine threads – in fact, many lumps of peat I have seen thoroughly impregnated with pure copper, one of which I assayed and it gave 90% of pure copper' (Thomas 1953). Also relevant is an observation by Professor G.J. Allman that 'some idea of the antiquity of these singular mining operations may be formed from the fact of some of the old rubbish being now found near the mouth of the cuttings [trench mines], with a covering of more than two feet of apparently naturally formed peat' (Allman 1848, 65). This indicates some growth of peat over surface deposits of rock spoil produced by the working of these mines.

Similar observations were made by the Quaternary scientist, Frank Mitchell, during a visit to the mine in 1947 in the company of Professor Sean P. Ó Ríordáin. At one location, Mitchell recorded a 0.45m thickness of natural peat beneath a surface layer of nineteenth-century spoil. Below this, he noted a 0.13m thick layer of grey-green sandy clay ('Swanton's slime') containing a broken stone mining hammer. That sediment overlays a 0.4–0.98m thick lower peat formation on bedrock (reported in Jackson 1984, 47). As was the nature of such studies, at the time the unpublished palynological assessment undertaken by Mitchell focused exclusively on arboreal taxa and as such presents a limited picture of the ecological history of the site. His pollen profile does demonstrate that the arboreal component of the local vegetation was initially dominated by Scots pine, with lower values of hazel, oak, elm and alder also evidenced (Mitchell typescript, Department of Archaeology, University College Cork). The prevalence of Scots pine in the local landscape decreased from 0.90m, with hazel increasing to become the principle arboreal taxon at Derrycarhoon. Although the absence of radiocarbon dates in the Mitchell study prevents robust comparison between the two profiles, a similar pattern of ecological change is noted in this study (see below).

The relevance of these peat associations for the dating of early copper mines at Derrycarhoon has been considered from three perspectives: the initiation of peat growth, the rate of peat accumulation, and palynological information (Jackson 1984, 47; O'Brien 1987, 60–3; O'Brien 1989, 13–14). Numerous studies confirm that initiation of blanket peat growth is diachronous across the south-west region, while the rate of accumulation is also specific to depositional environments. That said, the significant depth of undisturbed peat recorded in the Derrycarhoon workings, exceeding 3m in some instances, together with the aforementioned peat associations on or close to surface spoil, is a strong indication of the antiquity of these mines. Jackson (1984, 47) considered Mitchell's recording of pine pollen in peat overlying early mine sediment relevant to the dating of the mine, given the widespread disappearance of pine during the late prehistoric period (Bradshaw and Browne 1987), and locally in the Mizen Peninsula (Mighall *et al.* 2004). Some studies in Cork and Kerry, however, indicate the survival of pine in small stands in some areas (e.g. Buzer 1980; Mitchell 1988), thereby reducing its value as a chronological marker.

Given these uncertainties, it was necessary to undertake palaeoecological analysis to understand the significance of mine–peat associations at Derrycarhoon. The 1846 exploration, and several phases of mining and prospecting that followed into the twentieth century, disturbed or destroyed many of those peat deposits. Further damage was caused by deep ploughing for conifer forestry in recent decades. While that is a significant loss, recent survey confirms that undisturbed peat deposits survive in some of the early trench mines, beneath redeposited spoil in the central mine area, and in a few small basins on the periphery (O'Brien 2019).

Palynology at Derrycarhoon mine

In November 2018, the authors sampled a 2.12m core of peat on the south-west side of Derrycarhoon mine (Fig. 2). This was taken using a 0.50m long Russian corer with a cylinder diameter of 0.06m. All cores were placed in labelled guttering and sealed in plastic wrap in the field and stored at 4°C in the laboratory. The cores were cleaned in the laboratory and the stratigraphy was described using the Troels-Smith (1955) recording system. Sub-sampling for pollen analysis was carried out at depth intervals of 0.02m or 0.04m.

Radiocarbon dating and age-depth modelling

Six samples (nine measurements in total) were analysed at Queen's University Belfast (UBA-) by AMS radiocarbon dating. All measurements were obtained from organic sediment samples, with some duplicate measurements on the humin (the acid and alkali-insoluble) and humic (alkali-soluble, acid insoluble) fractions (Cook *et al.* 1998, 21). These duplicate measurements were obtained to test the reliability of sediment-derived radiocarbon determinations (cf. Brock *et al.* 2011), with the statistical consistency (Ward and Wilson 1978) of each paired date assessed using the OxCal (Bronk Ramsey 2009a) programme.

The resulting radiocarbon determinations are presented as conventional radiocarbon ages (Stuiver and Polach 1977) and are quoted in accordance with the international standard established by the Trondheim Convention (Stuiver and Kra 1986). The calibrations of these results have been calculated using the IntCal20 data-set (Reimer *et al.* 2020) and the computer programme OxCal v4.4 (Bronk Ramsey 2009a). The calibrated date ranges are cited in the form recommended by Mook (1986), with the end points rounded outward to ten years. They were calculated using the maximum intercept method (Stuiver and Reimer 1986) and the graphical distribution of the calibrated result was derived from the probability method (Stuiver and Reimer 1993). All radiocarbon dates are cited at 95.4% confidence, unless stated otherwise.

In order to refine the chronology of palynological features and extend the chronological framework to changes which fall between dated horizons, a Bayesian approach to age-depth modelling was employed (Buck *et al.* 1992). The approach taken here uses the OxCal v4.4 software (Bronk Ramsey 2009a), and the *P-Sequence* function (Bronk Ramsey 2008; Bronk Ramsey and Lee 2013) was chosen to allow for a Poisson process, or a potentially random rate, of sediment formation. The prior information for the deposition rate was defined as log_10(k/k_0) where k_0 = 1. This allows k to take any value from 0.01–100. The value used was estimated from the radiocarbon dates following the approach outlined in Blockley *et al.* (2007; 2008). The *Outlier*() function in OxCal (Bronk Ramsey 2009b) was used to identify any measurements that were statistically defined as outliers at a 0.05 probability (one in twenty chance).

Palynological analysis

Sub-samples of 0.01m³ thickness were prepared for pollen analyses following standard techniques including KOH digestion, HF treatment and acetylation (Moore *et al.* 1991). Pollen concentrations were established by adding a known concentration of *Lycopodium clavatum* spore (batch number 161018201) to the samples before treatment (Stockmarr 1971). A minimum pollen sum of 500 Total Land Pollen (TLP) grains, excluding spores and aquatics, was employed. Pollen grains were identified mainly using the key of Moore *et al.* (1991) and Bennett (1995), with reference to Fægri *et al.* (1989). Pollen and spore identification was made to the lowest taxonomic level possible using the available references and following the nomenclature of Stace (1997), with suggestions from Bennett *et al.* (1994). The programmes TILIA and TILIA-GRAPH (Grimm 2013) were used to construct spreadsheets and pollen diagrams. Local pollen assemble zones (LPAZ) were defined based on visible changes in the pollen record.

Loss on ignition (LoI)

Sediment samples (*c.*0.05m³) were taken at 0.02m intervals to calculate loss on ignition (LoI %). The samples were dried for 24 hours at 105˚C and subsequently transferred to porcelain crucibles and ashed for four hours at 550˚C (after Bengtsson and Enell, 1986; Heiri *et al.* 2001). Loss on ignition diagrams were constructed using the TILIA programme (Grimm 2013), with zonation of the loss on ignition data corresponding to the pollen assemblage zones.

Results

Lithostratigraphy

The results of the core lithology are presented in Table 1 and consisted of dark brown, humified peat (depth of 0.1–1.71m from top) with two distinct sections with silt bands recorded between 0.58–0.67m and 1.59–1.66m from top. Below this, the sediment consisted of black, well humified peat (1.71–2.12m).

Radiocarbon dating and age-depth modelling

Two pairs of measurements from 0.96m (*UBA-39922* and *UBA-39923*) and 2.11m (*UBA-39918* and *UBA-39919*) are not statistically consistent (see Table 2). In both instances the humic fraction is younger than the humin fraction, likely caused by the downwards penetration of water-soluble humic acids from above; therefore the humin fractions (*UBA-39922* and *UBA-39918*) have been used in the modelling process for these depths. Measurement *UBA-40627* was identified

TABLE 1—Lithostratigraphic record of sediments from Derrycarhoon.

Depth (m)	*Troels-Smith description*	*Sediment description*
0.10–0.58	nig 2; strf 1; elas 2; sicc 3; lim 1; hum 3.	Dark brown, well humified peat.
0.58–0.67	nig 2; strf 2; elas 1; sicc 3; lim 3; hum 3; Ag 2.	Dark brown, well humified peat with silt bands.
0.67–1.59	nig 2; strf 0; elas 3; sicc 3; lim 1; hum 3.	Dark brown, well humified peat.
1.59–1.71	nig 2; strf 1; elas 2; sicc 3; lim 2; hum 3; Ag 1.	Dark brown, well humified peat with silt bands.
1.71–2.12	nig 4; strf 1; elas 1; sicc 1; lim 0; hum 2.	Black, well humified peat.

TABLE 2—Radiocarbon dates for core DER, Derrycarhoon.

Lab code	*Dated material*	*^{14}C Age (BP)*	*Depth (m)*
UBA-40627	Organic sediment (humin fraction)	4072±34	0.22–0.23
UBA-40626	Organic sediment (humin fraction)	2531±21	0.42–0.43
UBA-40625	Organic sediment (humin fraction)	2881±53	0.62–0.63
UBA-39922	Organic sediment (humin fraction)	3792±31	0.96–0.97
UBA-39923	Organic sediment (humic fraction)	3654±31	0.96–0.97
Statistically inconsistent measurements (T'=9.9; T' (5%)=3.8%; v=1).			
UBA-39920	Organic sediment (humin fraction)	7382±36	1.62–1.63
UBA-39921	Organic sediment (humic fraction)	7434±40	1.62–1.63
Statistically consistent measurements (T'=0.9; T' (5%)=3.8%; v=1). Weighted mean 7405±27			
UBA-39918	Organic sediment (humin fraction)	11947±92	2.11–2.12
UBA-39919	Organic sediment (humic fraction)	11718±66	2.11–2.12
Statistically inconsistent measurements (T'=4.1; T' (5%)=3.8%; v=1).			

as a possible outlier and has been excluded from the model; this determination was considerably older than those below it, suggesting that reworked material had been incorporated into the profile.

An age depth model (Bronk Ramsey 2008) for the profile was constructed to provide a chronology for the sequence. The *P-Sequence* model (Fig. 5) has good agreement (A_{model}=99.5) and is used to provide estimates for the boundaries between the local pollen assemblage zones (Table 3). The pollen sequence can be estimated to cover a period of *11070–13820 years* (*95.4% probability*), or *11310–12950 years* (*68.2% probability*), covering almost the entirety of the Holocene. Estimates derived from the age-depth model suggest a rather slow accumulation rate, with an average deposition rate of *1–2cm/100yr* between the upper and basal radiocarbon measurements. Alternatively, it can be estimated that *64–67 years* are represented in every centimetre. However,

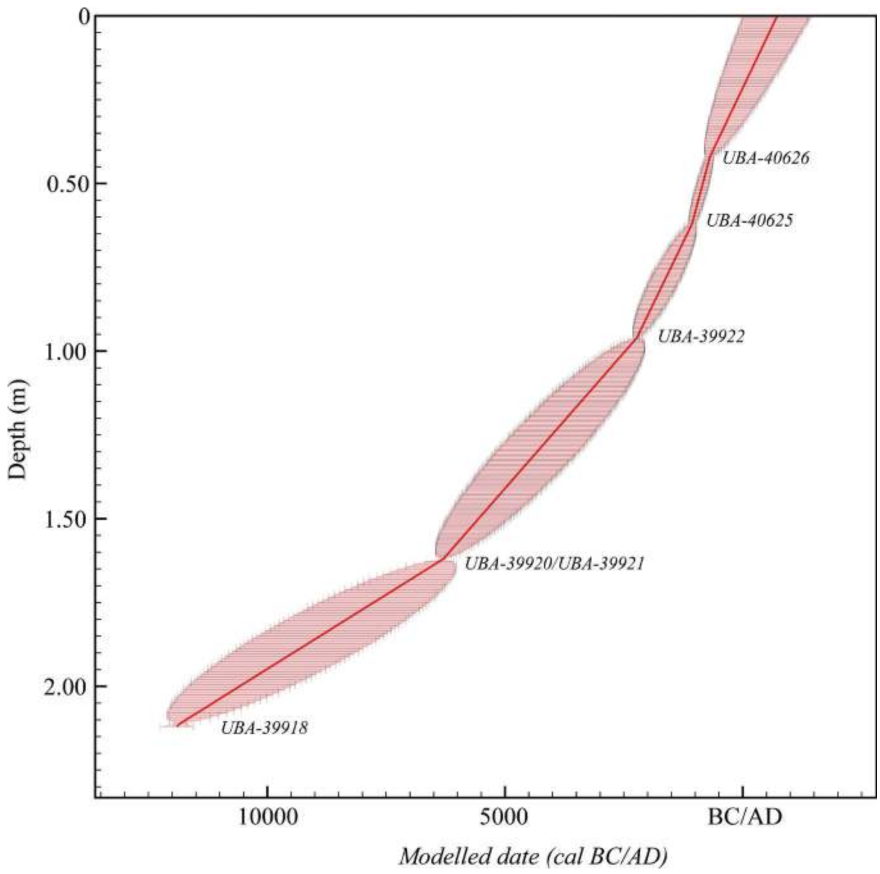

FIG. 5—Age-depth model for DER core, Derrycarhoon mine.

the sedimentation rate varies throughout the core (see Fig. 6), with particularly slow accumulation rates of *c.*0.01–0.02cm/yr recorded in the lower core between 2.12m and 0.96m (*c.*11900–2240 BC). The *P_Sequence* deposition model (Bronk Ramsey 2008) indicates that accumulation rates increased to *c.*0.03cm/yr between 0.95m and 0.62m (*c.*2190–1200 BC), increasing to *c.*0.06cm/yr between 0.61m and 0.43m (*c.*1050–710 BC), before returning to a rate of *c.*0.03cm/yr after 0.42m (*c.*690 BC).

Palynological analysis

Pollen data are presented in Table 3 and the percentage pollen diagram DER (Fig. 7) and are interpreted below. The pollen profile has been divided in ten local pollen assemblage zones (LPAZ), and boundary dates are derived from the age-depth model shown in Fig. 5. The degree of pollen preservation was so poor, and the concentration so low, in the basal 0.26m of the core that no reliable interpretation can be drawn from this dataset. Therefore, only the pollen record from the upper 1.86m of the core is presented here.

TABLE 3—Summary of pollen and loss on ignition data from Derrycarhoon pollen core.

LPAZ/Depth (m)	*Date*	*Cultural period*	*Main pollen features*	*Loss on ignition (LoI)*
DER-10 0.10–0.25m	*c.*480 cal AD–70 cal BC.	*Late Iron Age to Early Medieval*	*Corylus* increasing to *c.*50% across LPAZ. NAP values reduced to *c.*12%, primarily Poaceae at *c.*10%. *Plantago lanceolata* ceases at base of LPAZ, recorded again at *c.*1% towards top. Sporadic Asteraceae (Asteroideae/Cardueae) undif., *Filipendula* and *Rumex acetosa/acetosella* throughout. Ericaceae decreasing to *c.*5%, increase in Cyperaceae to *c.*10%. TLP concentration fluctuates between *c.*60 $\times10^3$ and *c.*100 $\times10^3$ across LPAZ.	Organic material (OM) stable at *c.*70% across LPAZ but drops to *c.*60% at 0.24m and *c.*55% at 0.18m.
DER-9 0.25–0.53m	*c.*70–900 cal BC.	*Late Bronze Age to Late Iron Age*	*Corylus* and *Quercus* values reduced to *c.*30% and *c.*10% respectively. NAP values peak at *c.*25%, primarily Poaceae at *c.*20%, and *Plantago lanceolata c.*3%. Asteraceae (Lactuceae) undif., Apiaceae, Asteraceae (Asteroideae/Cardueae) undif., *Filipendula* and *Rumex acetosa/acetosella* also present throughout. Ericaceae vales high (*c.*30%). Peak in charcoal *c.*26% (TLP + S) at 0.36m. TLP concentration high *c.*150 $\times10^3$ across LPAZ.	OM declining to <60% by 0.46m before recovering to >70% from 0.40m.
DER-8 0.53–0.65m	*c.*900–1170 cal BC.	*Late Bronze Age*	*Pinus* continues to decline across the LPAZ to <1%, *Corylus* increases to *c.*40%, while other AP taxa stable. NAP values stable at *c.*15%. Ericaceae increasing across the LPAZ to *c.*35%, concomitant with a decrease in Cyperaceae to *c.*5% and *Sphagnum* spp. to *c.*10% (TLP + S). Charcoal low through LPAZ. TLP concentration increases from *c.*100 $\times10^3$ to *c.*160 $\times10^3$ at top of LPAZ.	OM drops to *c.*40% by 0.62m. Recovering to *c.*75% at top of LPAZ.
DER-7 0.65–0.75m	*c.*1170–1510 cal BC.	*Middle Bronze Age*	*Pinus* values low, *c.*7%, while Cyperaceae and *Sphagnum* spp. high, *c.*25%. and *c.*30% (TLP + S) respectively across LPAZ. Increase in NAP values, averaging *c.*12%, primarily Poaceae (*c.*9%), but Asteraceae (Lactuceae) undif., Apiaceae, Asteraceae (Asteroideae/Cardueae) undif., *Filipendula, Mentha*-type, *Potentilla*-type and *Succisa* all recorded across the LPAZ. Small increase in charcoal at base of LPAZ.TLP concentration increases from *c.*100 $\times10^3$ to *c.*160 $\times10^3$ at top of LPAZ.	OM stable at 75%, before declining from 0.66m.
DER-6 0.75–0.82m	*c.*1510–1750 cal BC.		*Pinus* drops to *c.*10%. Increase in Cyperaceae to *c.*40% concomitant with a reduction in Ericaceae to *c.*5%. Overall NAP values reduced to *c.*8% while *Plantago lanceolata* curve ceases. TLP concentration ranges from *c.*100 $\times10^3$ to *c.*150 $\times10^3$, across LPAZ.	OM decreasing to <70% at the top of LPAZ.

(*Continued*)

TABLE 3—(*Continued*)

DER-5 0.82–0.97m	*c.*1750–2290 cal. BC.	*Early Bronze Age*	*Pinus* and *Quercus* reduced to *c.*35% and *c.*10% respectively, increase in *Corylus* to *c.*30%, other AP relatively stable. NAP values increase to *c.*20%, dominated by Poaceae (10%), *Plantago lanceolata* (*c.*4%) *Filipendula* (1%)*, Succisa* (1%). Apiaceae, Asteraceae (Asteroideae/Cardueae) undif., Asteraceae (Lactuceae) undif. and *Potentilla*-type also present. Ericaceae increases to *c.*15% midway through LPAZ. TLP concentration high, *c.*150 $\times 10^3$, across LPAZ.	OM stable at *c.*80% across LPAZ.
DER-4 0.97–1.38m	*c.*2290–4820 cal. BC.	*Late Mesolithic to Early Bronze Age*	*Pinus* continues to increase, peaking at *c.*57% at 1.16m, *c.*45% by the top of LPAZ. *Quercus* values stable at *c.*20%, *Corylus* reduced to *c.*15%, while low values of *Taxus* and *Ulmus* (both <1%) are recorded. *Alnus* appears low, but continuously (*c.*2%) from base of LPAZ. NAP values low, mainly Poaceae (*c.*4%) with sporadic occurrence of Asteraceae (Asteroideae/Cardueae) undif., Asteraceae (Lactuceae) undif., *Filipendula* and *Succisa*. *Osmunda regalis* (*c.*2% TLP + S) and *Polypodium* (*c.*7% TLP + S), while *Sphagnum* spp. (*c.*12% TLP + S) increases midway through the LPAZ. TLP concentration high, ranging from *c.*120 $\times 10^3$ to 200 $\times 10^3$, across LPAZ.	OM increasing to *c.*90% before declining to <60% by 1.04m before recovering to *c.*80% by top of LPAZ.
DER-3 1.38–1.58m	*c.*4820–6050 cal. BC.	*Late Mesolithic*	*Quercus* (to *c.*15%) and *Pinus* (to *c.*38%) expanding across LPAZ, *Corylus* and *Salix* declining to *c.*30% and <1% respectively, while *Betula* remains stable at *c.*5%. NAP values low (*c.*5%). TLP concentration increases to *c.*150 $\times 10^3$ at the base of the LPAZ, fluctuating between *c.*75 $\times 10^3$ and *c.*100 $\times 10^3$ thereafter.	OM increasing to *c.*90% by 1.44m before dropping to *c.*80% by close of LPAZ.
DER-2 1.58–1.78m	*c.*6050–8100 cal. BC.	*Early Mesolithic*	*Corylus* expanding rapidly across the LPAZ to *c.*60%, *Betula* greatly reduced (*c.*5%). *Quercus* (*c.*6%), *Salix* (*c.*10%) and *Pinus* (*c.*8%) present throughout. Charcoal values low. TLP concentration high, average *c.*150 $\times 10^3$, before declining sharply to *c.*50 $\times 10^3$ at the top of the LPAZ.	OM declining to *c.*65% at base of LPAZ, dropping sharply to <40% at 1.62m before recovering to *c.*80% by 1.58m.
DER-1 1.78–1.86m	*c.*8100–9010 cal. BC.		AP values high *c.*80%, dominated by *Betula* *c.*70% and *Salix* *c.*8%. *Corylus* recorded <5% at the top of LPAZ. NAP values reduced from *c.*20 to <3% by close of LPAZ. *Polypodium* (*c.*4 TLP + S) recorded at base of LPAZ, peak in charcoal at 1.80m (*c.*5% TLP + S). TLP concentration increasing across the LPAZ from *c.*35 $\times 10^3$ to *c.*150 $\times 10^3$.	OM stable at *c.*90% across LPAZ.

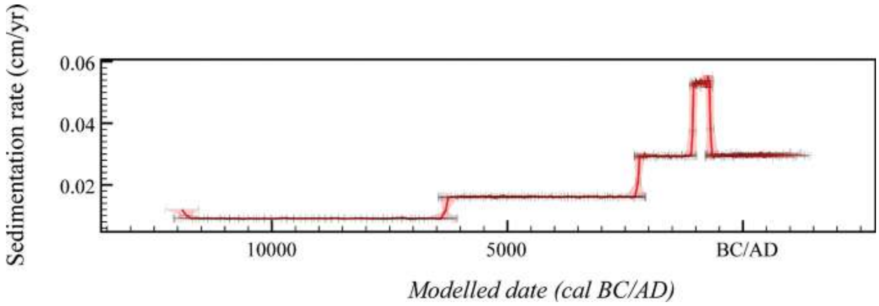

FIG. 6—Sedimentary rate for DER core determined by the Bayesian age-depth model.

Loss on ignition (LoI)

The results of loss on ignition presented in Table 3 and Fig. 7 are interpreted below. Zonation for LoI data follows the LPAZ used in the pollen diagram.

Interpretation

DER-1, 1.86–1.78m, c.9010–8100 BC

Arboreal (AP) taxa (*c.*45–80%), primarily *Betula* (birch) and *Salix* (willow), dominate the early Holocene landscape at Derrycarhoon, with *Corylus avellana*-type (probably largely hazel) constituting a minor component of the vegetation by the top of the LPAZ. Open grassland environments are initially evidenced with non-arboreal taxa (NAP), excluding Cyperaceae (sedges), values of *c.*20%, but these are greatly reduced by the close of the LPAZ. High loss on ignition (LoI) values (*c.*90%) indicate considerable mineral soil stability across the LPAZ.

DER-2, 1.78–1.58m, c.8100–6050 BC

Zone DER-2 is characterised by the replacement of birch (*c.*70% to *c.*5%) by hazel (<5% to *c.*60%) as the dominant taxa. Willow values remain stable at *c.*10%, while *Quercus* (oak) and *Pinus sylvestris* (Scots pine) become established in the local woodland. NAP values remain low, indicating that open environments were limited throughout the LPAZ. A marked reduction in LoI values to <40% is recorded at 1.62m, likely indicating increased mineral in-wash from higher altitudes to the north of the sampling basin. However, this does not correlate with any significant changes in vegetation composition, although overall pollen concentration is reduced.

DER-3, 1.58–1.38m, c.6050–4820 BC

Values of oak (to *c.*13%) and Scots pine (to *c.*38%) increase across the LPAZ, at the expense of hazel and willow (to *c.*20% and <1% respectively), indicating the expansion of these tall canopy trees. LoI values increase to *c.*90% by 1.44m, indicating a reduction in minerogenic in-wash compared to the previous LPAZ.

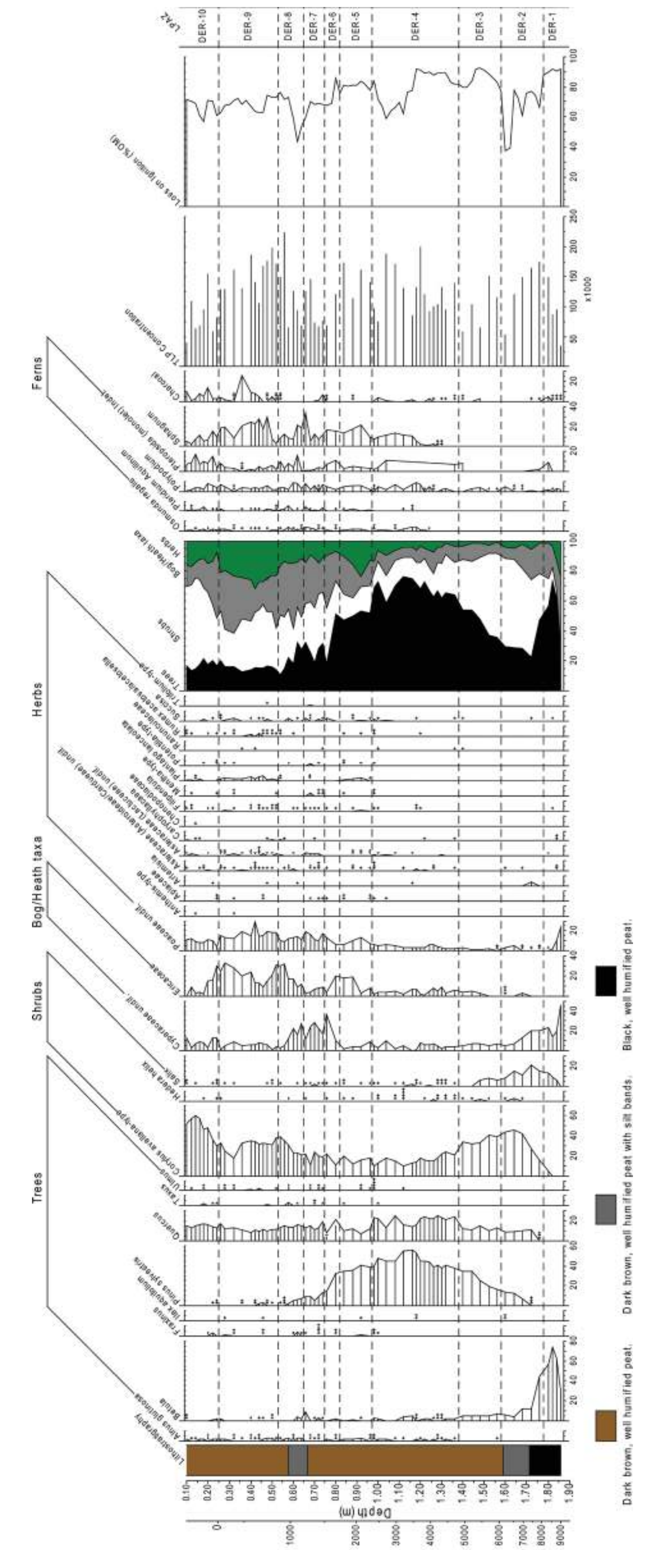

FIG. 7—Pollen percentage diagram for DER core, Derrycarhoon mine.

DER-4, 1.38–0.97m, c.4820–2290 BC

Scots pine continues to increase across the LPAZ peaking at *c.*57% before reducing to *c.*45% by the close of the LPAZ. Oak remains stable at *c.*20%, while both hazel (*c.*15%) and birch (*c.*1%) are further reduced, indicating the development of a mixed pine–oak dominated woodland canopy. *Alnus* (alder) begins to appear continuously, although the low values (*c.*2%) raise the possibility that this represents a regional rather than a local presence (Lisitsyna *et al.* 2011). NAP values remain low, although the presence of grasses (*c.*4%) and the sporadic occurrence of Apiaceae (carrot family), Asteraceae (Lactuceae) undif. (dandelions), Asteraceae (Asteroideae/Cardueae) undif. (daisies), *Filipendula* (meadowsweet) and *Succisa pratensis* (devil's bit scabious) suggest limited areas of wet grassland near the sampling site. LoI declines to <60% by 1.04m, but again this does not correspond with significant changes in vegetation composition.

DER-5, 0.97–0.82m, c.2290–1750 BC

Zone DER-5 is characterised by a reduction in Scots pine and oak to *c.*35% and *c.*10% respectively, while hazel increases to *c.*30%. NAP values increase *c.*20%, primarily grasses, *c.*10%, and *Plantago lanceolata* (ribwort plantain), *c.*4%. increases of these herbaceous taxa, in addition to the continuous occurrence of meadowsweet, devil's bit scabious, carrot family, daisies, dandelions and *Potentilla*-type (cinquefoil) indicate the presence of pastoral habitats at Derrycarhoon. Ericaceae (heather) increases midway through the LPAZ to *c.*15%, possibly indicating a shift to drier bog surface conditions and development of dry siliceous heath at Derrycarhoon.

DER-6, 0.82–0.75m, c.1750–1510 BC

Scots pine begins to decline at the base of the LPAZ from *c.*35% to *c.*10%. NAP values drop to *c.*7%, ribwort plantain representation ceases and other ruderal taxa are recorded only sporadically suggesting a reduction in pastoral habitats. Heather values are also reduced in correlation with an increase in sedges to *c.*40%, and with the high values of *Sphagnum* spp. bog moss, *c.*15% (TLP + S), suggests a shift to wetter surface conditions.

DER-7, 0.75–0.65m, c.1510–1170 BC

Following the reduction in Scots pine values in the previous LPAZ, NAP values rise to *c.*15%. This increase in NAP is primarily in values of grasses (*c.*12%), and with the continuous presence of herbaceous taxa such as meadowsweet, *Mentha*-type (mint family), cinquefoil and devil's bit scabious indicate an increase in wet grasslands habitats at Derrycarhoon.

DER-8, 0.65–0.53m, c.1170–900 BC

Scots pine continues to decline across the LPAZ to <1%, with hazel increasing to *c.*40% and oak remaining stable at *c.*20%. NAP values remain stable at *c.*15%, heather increases to *c.*35%, concomitant with a decrease in sedges to *c.*5% and bog moss to *c.*10% (TLP + S), indicating a return to drier surface conditions. LoI values decline to <40% from the base of the LPAZ, before recovering to *c.*75%; however, the drop in LoI values does not appear to correspond with reductions in the woodland canopy.

DER-9, 0.53–0.25m, c.900–70 BC

Hazel and oak values are reduced to *c.*30% and *c.*10% respectively. NAP values increase to peak values of *c.*25%. This is primarily evidenced in values of grasses at *c.*18% and ribwort plantain at *c.*3%. The values for these herbaceous taxa in addition to dandelions (*c.*3%), daisies, meadowsweet and docks suggest the presence of pastoral habitats at Derrycarhoon during LPAZ DER-9.

DER-10, 0.25–0.10m, c.70 BC– AD 480

Zone DER-10 is characterised by increased hazel to *c.*55%, while NAP values are reduced to *c.*12%, suggesting a period of woodland regeneration and the development of a dense hazel-dominated scrub woodland. However, the occurrence of ribwort plantain (*c.*1%) at the top of the LPAZ, in addition to daisies, meadowsweet and docks would suggest the continued presence of limited pastoral habitats at Derrycarhoon.

Discussion

The Derrycarhoon percentage pollen diagram provides a record of vegetation change from the early Mesolithic (*c.*9010 BC) through to the early Medieval period (*c.*AD 480), a period of *c.*9490 years. This represents a succession of phases of expansions and contractions of arboreal and non-arboreal pollen. With one exception (see below), these fluctuations appear to predominantly reflect human disturbance, characterised by increases in taxa indicative of open, pastoral environments and disturbed soils (especially ribwort plantain, grasses, daisies and dandelions) and falls in values of tree/shrub pollen showing contraction in woodland. It should be noted, however, that total non-arboreal pollen percentages rarely exceeds 20% for the entire record implying that although herbaceous taxa are probably underrepresented palynologically (*cf.* Caseldine and Fyfe 2006) wood/scrub cover remained of greater extent than open ground, even during episodes of apparent human impact and woodland clearance (see below). Episodes of increased human activity seem to have impacted most on populations of hazel and oak, with Scots pine affected in some periods, especially during the late Chalcolithic (*c.*2300 BC).

Early Holocene vegetation change

The earliest Holocene landscape at Derrycarhoon was dominated by scrub woodland, initially birch and willow, with the former being replaced by hazel from *c.*7500 BC. Scots pine and oak become established from *c.*7000 BC, before expanding to become the dominant woodland taxa similar to other profiles from south-west Ireland (Mitchell 2006; Mighall *et al.* 2007; Overland and O'Connell 2008; Kearney 2019). In contrast to suggestions of woodland disturbances and Mesolithic anthropogenic activity elsewhere in the region (Mighall *et al.* 2007), the low levels of herbaceous taxa evidenced at Derrycarhoon indicate the woodland canopy remained closed throughout this period.

Potential evidence for the 8.2kyr climate anomaly (Alley *et al*. 1997; Alley and Ágústsdóttir 2005) is noted at Derrycarhoon between *c.*6300 BC and *c.*6150 BC, with marked alterations in pollen concentration and LoI data, although no evidence for changes in local vegetation is recorded. However, the possibility that this falls between sampling intervals or that the relatively slow accumulation rate in this section of the core hindered the detection of such changes cannot be overlooked. The sharp decline in pollen concentration points to lower pollen productivity, probably resulting from lower temperatures (cf. Ghilardi and O'Connell 2012), while increased minerogenic content suggests soil instability during this anomaly. Similar patterns suggested to represent ecological responses to climate events are evidenced from elsewhere in Ireland (e.g. Huang 2002; Ghilardi and O'Connell 2012). The signal at Derrycarhoon correlates with the climate anomalies recorded in the Greenland ice-core records (Rasmussen *et al*. 2007; Thomas *et al.* 2007).

From *c.*6100 BC, pollen concentration values increase and minerogenic content decreases, suggesting more favourable thermal conditions and less soil erosion. Scots pine and oak expand to become the dominant taxa, indicating the development of a mixed conifer-broadleaf woodland. The expansion of alder, which characterises the beginning of the Atlantic period in north-west Europe was unusually absent at Derrycarhoon. While alder became established across much of Ireland from *c.*5000 BC (Birks 1989), several studies suggest a later date for the alder expansion in the south-west region (Barnosky 1988; Mitchell 1989, Mighall *et al.* 2004; 2007; Kearney 2019). The general absence of spatial coherence of the alder expansion within Britain and Ireland appears to be very specific in comparison to the generally observed 'stepping stone' nature of expansion for other arboreal taxa (Bennett and Birks 1990; Mitchell 2006). This suggests the delayed alder expansion in south-west Ireland resulted from environmental constraints rather than the effect of slow colonisation, which may account for the delayed presence of alder at Derrycarhoon.

The 'pine decline'

The reduction in Scots pine at Derrycarhoon from *c.*1700 BC probably coincides with the beginnings of the 'pine decline' in the region. The decline of Scots pine is well documented across much of Ireland, northern Scotland and England (e.g. Bennett 1984; Bridge *et al.* 1990; Gear and Huntley 1991; Pilcher *et al.* 1995; Lageard *et al.* 1999; Mighall *et al.* 2004), with numerous competing hypotheses proposed for the cause of this reduction, including anthropogenic activity (Dodson 1990, Tipping *et al.* 2008), changing hydrological conditions and the spread of blanket peat (Bradshaw and Browne 1987). Recent studies in the region (Mighall *et al.* 2004) have suggested soil mineral deficiency and increased surface wetness, possibly due to climate change in the form of increased precipitation, created conditions unsuitable for Scots pine growth. Evidence from Derrycarhoon suggests a similar causal factor, with a short-lived increase in wet-loving mire taxa as Scots pine values begin to decline. This expansion of wet-loving taxa is also indicated across the wider south-west region (Barnosky 1988; Dodson 1990; Mighall and Lageard 1999; Kearney 2019), while Monk (1993) suggests that the spread of blanket peat commenced across the region at this time. That would indicate that changing local hydrological conditions and the spread of blanket peat may have contributed to the onset of the 'pine decline' at Derrycarhoon.

Bronze Age farming and mining impacts

While evidence of anthropogenic activity is noted elsewhere in south-west Ireland for the Mesolithic and Neolithic periods (Buzer 1980; Mighall *et al.* 2007; Kearney 2019), it is not until the Chalcolithic/Early Bronze Age that the first evidence for such activity is recorded at Derrycarhoon. Increased representation of herbaceous taxa indicative of farming (cf. Behre 1981; 1986) is evidenced between *c.*2300 BC and *c.*1800 BC, coinciding with a reduction in oak and to a lesser degree hazel and Scots pine. This is interpreted as evidence of pastoral farming in the locality. Palynological evidence from other Irish investigations (Ghilardi and O'Connell 2013; Chique *et al.* 2017; Spencer *et al.* 2019; Stolze and Monecke 2020) also provide evidence of land-use intensification and pastoral farming during that period.

However, in contrast to many of those records (e.g. Ghilardi and O'Connell 2013; Chique *et al.* 2017, Taylor *et al.* 2018), and others from south-west Ireland (Mighall *et al.* 2007; Overland and O'Connell 2008; Kearney 2019), evidence for agriculture at Derrycarhoon becomes more muted after *c.*1800 BC into the Middle Bronze Age. Herbaceous taxa indicative of farming are greatly reduced, and ribwort plantain ceases to be recorded at Derrycarhoon until the Late Bronze Age, *c.*900 BC, suggesting a cessation or at least a reduction of agricultural activity. Land-use dynamics across the south-west appear to be quite variable, however, as evidence for both pastoral and arable farming during the Middle Bronze Age is noted farther west on the Mizen peninsula, at Mount Gabriel (Mighall *et al*. 2000), Cadogan's Bog (Mighall and Lageard 1999) and Arderrawinny (Kearney 2019). An intense phase of agricultural activity *c.*1450–1050 BC is also recorded in the Beara peninsula (Overland and O'Connell 2008).

It is during this period of reduced agricultural activity that copper mining commenced at Derrycarhoon. There is no palynological evidence to suggest that mining there, *c.*1300–1000 BC, impacted greatly on local vegetation. Indeed, both hazel and oak recover during this period, especially the former from *c.*1250 BC, while reductions in overall NAP and the absence of ribwort plantain indicate that woodland clearance and farming was not occurring when mining activity was being undertaken at the site. This compares with pollen records from Bronze Age copper mines on Mount Gabriel near Derrycarhoon, and in Wales, which indicate that woodland disturbances associated with mining were small-scale and had little long-lasting impact on local vegetation (Mighall and Chambers 1993; Mighall *et al.* 2000: 2010). Potential evidence for Bronze Age mining at Derrycarhoon is recorded in the LoI data, with a marked increase in minerogenic in-wash from *c.*1200 BC, similar to fluctuations in LoI records noted in association with Bronze Age, Iron Age and Roman mining activity in Wales (Mighall *et al.* 2009; 2017).

An upsurge in agricultural activity is noted at Derrycarhoon from *c.*900 BC, where again reductions in the oak–hazel woodland are recorded and herbaceous taxa indicative of farming, especially ribwort plantain, greatly increased. This corresponds with several records across the region and elsewhere (Overland and O'Connell 2008; Ghilardi and O'Connell 2013; Spencer *et al.* 2019), which demonstrate increased human activity and an intensification of agricultural activity at the onset of the Late Bronze Age. The inferred intensity of pastoral activity and impact on woodland vegetation at Derrycarhoon is comparable to the land-use dynamics evidenced in the Early Bronze Age. Evidence of increased farming in the Late Bronze Age in Ireland corresponds with a general increase in archaeological visibility, which has been linked to an increased population (Plunkett 2009). However, the archaeological record from south-west Ireland is much more muted during the period, and as such does not mirror the palynological record from Derrycarhoon.

The 'Iron Age lull'

Palynological evidence indicates that pastoral farming continued to be practiced uninterrupted at Derrycarhoon well into the Iron Age, after which woodland regeneration and a reduction in human activity is exhibited from *c.*70 BC. This primarily represents an increase in hazel and to a lesser extent oak, while a notable reduction in herbaceous taxa indicates a period of reduced agricultural activity during the Late Iron Age. In this respect, the pollen profile from Derrycarhoon is consistent with many palynological records for this period (Weir 1993; 1995; Mitchell and Ryan 1997; Overland and O'Connell 2008; Chique *et al.* 2017). These record increased arboreal taxa, especially hazel, indicating forest regeneration, a decline in arable activity and contraction of open pastures from the beginning of the Late Iron Age, a phenomenon widely referred to the as the 'Late Iron Age lull'. The extent of woodland regeneration has been interpreted as indicating a collapse of the subsistence economy and a marked decline in population (Weir 1995), potentially resulting from environmental and climatic constraints (Baillie 1993; Baillie and Brown 2013).

This view is tempered by recent research that reveals the Late Iron Age lull to be a more time-transgressive phenomenon than previously observed, the onset of which varied considerably between *c.*200 BC–AD 200 (Coyle McClung 2013; Chique *et al.* 2017). The asynchronous nature of the 'lull' has led to suggestions that this reduction in activity represented a 'more gradual, socially-determined process involving both economic and political re-organisation' (Coyle McClung and Plunkett 2020, 154) rather than a climate driven 'event'. Notwithstanding whether it was culturally or climatically driven, the increase in hazel pollen recorded *c.*70 BC falls within the broad timescale for the perceived reduction in activity noted across the island, and therefore probably represents the Late Iron Age lull at Derrycarhoon.

Conclusions

As previously discussed, environmental records suggest several scenarios in relation to prehistoric copper mining, ranging from a sharp reduction of tree cover after mining commenced, to sustained or expanded levels of growth suggesting some form of woodland management. In most cases the impact on vegetation was relatively localised, and not easily distinguished from farming in the vicinity. The absence of evidence for substantial woodland clearance at mines where fire-setting was conducted may be explained either by an abundance of local woodland or careful management of limited resources to maintain regular fuel supply. In rare instances, wood may have been imported from distances outside the pollen catchment, or indeed the copper ore was transported to those sources for smelting.

There is much variation depending on the natural abundance of local woodland and the intensity and duration of the mining activity. In many instances the first significant impact on the natural vegetation of a mine location was due to agriculture. Where this coincided with the commencement of mining, as for example at Mount Gabriel and Ross Island in south-west Ireland, the pollen evidence indicates local farming that probably sustained the mining activity. At the other extreme is the enormous output from Bronze Age copper mines on Cyprus, and at Kargaly in Russia, where copper production had a long-term impact on the environment. Those examples aside, most Bronze Age copper mines did not have the same environmental impact as mining operations in the later historic period. This is borne out by analysis of heavy metal contamination in Greenland ice, which reveals very low levels of atmospheric pollution connected to prehistoric metal production in the Northern Hemisphere. The same ice cores indicate significant pollution coincident with large-scale Roman mining in the Mediterranean basin from the second century BC onwards (Ferrari *et al.* 1999).

The Derrycarhoon palynological study does not reveal any significant impact on local vegetation and environment as a consequence of copper mining, *c.*1300–1000 BC. That is consistent with the limited extent of the mine area, where it is unlikely that extensive clearance of woodland was necessary to expose copper-beds. Some felling of trees probably occurred at the mine, but not enough to register in the pollen record. This is consistent with a low level of wood use in the mine and its ancillary activities. The fact that fire-setting was not employed in rock extraction significantly reduced the amount of wood used, with supply for equipment, domestic fires, and possibly smelting, met by draw-felling of local woodland.

The study also confirms that accumulation of waste rock in the central mine area led to a slow release *c.*1250–1100 BC of minerogenic sediment into adjacent peat basins. This short-lived contamination was limited to the periphery of the mine area, probably with no long-lasting effects on vegetation. Soil and stream geochemical surveys indicate enhanced levels of copper and other metals across this townland (Keele 1969). Those anomalies are geological in origin, related to background values of sedimentary copper-beds and not to surface spoil in the prehistoric mine.

The present study confirms there was a significant human presence in the Derrycarhoon area during the Chalcolithic/Early Bronze Age, *c.*2300–1900 BC. That anthropogenic signal reduces significantly after 1900 BC, with little evidence of human activity in the immediate vicinity of the mine during the Middle and Late Bronze Age until around 900 BC. This is noteworthy as many pollen studies in the south-west region record significant human settlement and farming during the mid to late second millennium BC. This is evident in pollen records from the Beara Peninsula, which indicate a long-term reduction in tree cover and increased indicators of agriculture (Lynch 1981; Overland and O'Connell 2008). There are similar findings for the Mizen Peninsula, where a permanent reduction in tree cover can be linked to increased agriculture during the later second millennium BC (Mighall and Lageard 1999).

That does not mean there was no Bronze Age settlement in the hilly environs of Derrycarhoon mine, but that contemporary farming was probably concentrated in the lowland area toward the coast, 5–6km away. There are a significant number of ritual monuments of the 'stone circle complex' within 10km of the mine, including examples of axial stone circles, standing stone pairs and rows, single monoliths, and boulder-burials. Excavation confirms a later Bronze Age date for those monument types, spanning the period 1400–800 BC (O'Brien 2012, 182), suggesting that local examples were built around the same time as the mining activity at Derrycarhoon. They include a boulder-burial and stone pair excavated in 1989 by one of the authors at Ballycommane, 3.5km north-west of Derrycarhoon mine (O'Brien 1992, Fig. 7).

The results of this palynological study emphasise the variability of environmental signals created by prehistoric copper mines. The scale of mining at Derrycarhoon over two or three centuries, and its low level of wood consumption, explain why it does not register in the local pollen record for the later Bronze Age. While the same peat basin contains run-off sediment from surface mine spoil, that contamination was both short-lived and localised. The same study suggests there was no significant farm settlement in the vicinity of the mine, possibly because that hilly landscape was less favourable for agriculture than the coastal lowlands where the Derrycarhoon miners probably lived.

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