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Published PDF deposited in Coventry University's Repository

Original citation:

Mighall, T, Pittman, N, Foster, IDL, Ledger, P, Jordan, J, Cortizas, AM & Bateman, M 2023, 'The Midlands of England: Economic Backwater or an Agricultural Powerhouse? Environmental Evidence from Prehistory to Modern Times Recorded in Sediments from Aqualate Mere, Central England, UK', *Environmental Archaeology: The Journal of Human Palaeoecology*, vol. (In-Press), pp. (In-Press).

<https://doi.org/10.1080/14614103.2023.2187520>

DOI 10.1080/14614103.2023.2187520

ISSN 1461-4103

ESSN 1749-6314

Publisher: Taylor and Francis Group

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The Midlands of England: Economic Backwater or an Agricultural Powerhouse? Environmental Evidence from Prehistory to Modern Times Recorded in Sediments from Aqualate Mere, Central England, UK

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ABSTRACT

Archaeological and palaeoecological evidence relating to human activity in the English Midlands is scant compared to elsewhere in Britain. Knowledge of human activity in pre-Roman and Roman times is often fragmentary and disparate in parts of the region where it could be assumed that the resident population was small with little Roman impact. To examine these contentions, a palaeoenvironmental investigation from Aqualate Mere near Newport, Staffordshire, has been undertaken on the sediment record extending back to c. 1300 cal. BC. An analysis of microfossils, microscopic charcoal, sediment chemistry and mineral magnetism from a core dated by ¹⁴C, SCPs, ²¹⁰Pb and ¹³⁷Cs has provided an opportunity to reconstruct land use changes and atmospheric pollution from the later prehistoric period onwards. The results challenge the idea this region was a backwater as there is near-continuous agricultural activity around the mere since the Late Bronze Age through to modern times. This is characterised by phases of woodland decline, an intensification of farming, soil erosion, evidence for possible eutrophication and regional lead pollution.

ARTICLE HISTORY

Received 28 September 2022
Revised 30 January 2023
Accepted 28 February 2023

KEYWORDS

Prehistory; Romans; English Midlands; land-use; vegetation change; pollution

Introduction

Palaeolimnology has played an important role in improving our understanding of past environmental changes, including the growing impact of human activity. This includes recent and past pollution (e.g. Bindler et al. 2009; Fielding et al. 2020) and land use change such as deforestation and agriculture (e.g. Oldfield et al. 2003; Bradshaw et al. 2005). Such temporal data can be instructive for catchment rehabilitation, conservation, and water policy management (e.g. Bennion and Battarbee 2007; Pittam, Foster, and Mighall 2009; Bennion, Sayer, and Clarke 2018). While multi-proxy studies are increasingly common in palaeolimnology (Birks and Birks 2006), few studies have attempted to integrate biological and physical evidence with catchment source data and historical documentary evidence using a lake sediment-based approach to reconstruct human activity in the English Midlands (e.g. Oldfield et al. 2003; Pittam, Foster, and Mighall 2009), a region where knowledge of pre-

Roman and Roman human activity is often fragmentary and disparate (Blake, Dean, and Wardle 2018). Dark (1999) suggests that most pollen studies have not realised their full potential for reconstructing the environment of Roman Britain. This is true of the West Midlands of England, which is perceived to have been a 'backwater' compared to the militarised northern frontier zone, and southern Britain, where the Roman culture was adopted early and lingered longest (White and Hodder 2018). These regions also need to be studied to truly understand the regional diversity of Roman Britain (White and Hodder 2018).

This paper forms part of an investigation that aims to reconstruct Late Holocene environmental changes at Aqualate Mere (AQM) in Staffordshire, Central England (Figure 1A–C), using an integrated palaeoenvironmental approach. Lowland Staffordshire is a region with few archaeological excavations from prehistoric and Roman sites (Blake, Dean, and Wardle 2018) and a limited number of pollen sequences

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 Supplemental data for this article can be accessed online at <https://doi.org/10.1080/14614103.2023.2187520>.

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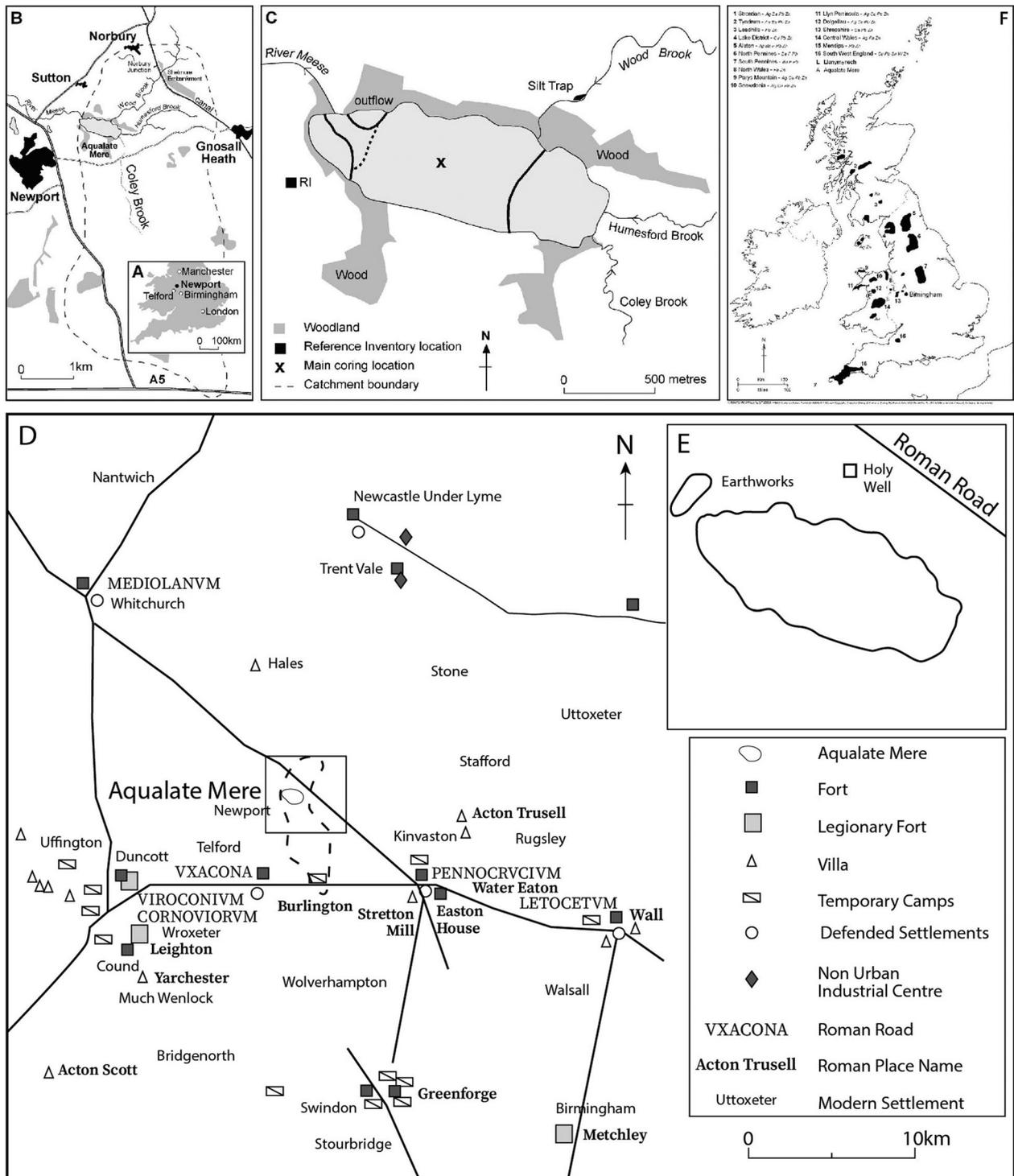


Figure 1. (a) Location of Aqualate Mere (near Newport) in the UK, (b) in the West Midlands of England, and (c) within its catchment; (d) overview of the distribution of the regional archaeology, and (e) the catchment archaeology; (f) position of the fieldsite relative to the major metaliferous orefields of Britain.

(Dark 1999). AQM is well placed to examine the impact of human activities on the landscape as it is surrounded by a range of archaeological monuments including roads, forts and villas, some occupied well into the 4th century AD and with evidence of continuity of settlement from the Iron Age through to the Roman period (Blake, Dean, and Wardle 2018) (Figure 1D). A Roman presence within the catchment of AQM is clearly visible (Figure 1E). A road to the

east of the mere crosses both Wood Brook and Humesford Brook and would have provided the arterial transport route between the Cantonal Capital for *Britannia Prima* at *Deva* (Chester) and the large military and urban centre at *Letocetvm* (Wall) along Watling Street (now the route of the A5). A possible earthwork is located to the west of the mere and a 'Holy Well' exists in the north of the Aqualate Hall Deer Park. There are also reports of burials under

Ancs Wood – a temporary encampment located in the south of the catchment at Burlington – and numerous fortifications and settlements; for example, at *Vxacona* (near Telford), *Pennocrvcivm* (near Cannock), Penkridge and Stretton, the latter both within 15 km of Stafford (Bartley and Morgan 1990). In this paper, we use pollen, non-pollen palynomorphs (NPPs), diatoms, geochemistry and mineral magnetic data from AQM to provide evidence of human activity during the last three millennia, and we compare our results with the archaeological and historical records to investigate the impact of prehistoric people and the Romans on the landscape surrounding the lake.

Site Description

AQM is a shallow, lowland lake with a water surface area of ca. 0.72 km² that formed in a kettle hole left by retreating Devensian ice (Pittam, Foster, and Mighall 2009). It is a Site of Special Scientific Interest (SSSI) and a National Nature Reserve (NNR). The lake is very shallow and has a mean depth of 1.20 m with a maximum depth of 1.40 m (Pittam 2006). The mere is regarded as internationally important by Natural England in its Geological Conservation Review (Glasser 2003; 2004). It is situated c. 2 km west of Newport, Staffordshire, UK (Figure 1A,B). The catchment of AQM encompasses c. 59 km² of predominantly agricultural land (Hutchinson 2005; Figure 1C). Previous research has focussed on the recent sedimentation history and the identification of sediment sources entering the lake (see Hutchinson 2005; Pittam, Foster, and Mighall 2009). Notwithstanding the factors that influence pollen recruitment source areas into a lake (e.g. Bonny 1976; Jacobson and Bradshaw 1981; Sugita 1993, 1994; Bunting et al. 2004; Pittam, Mighall, and Foster 2006;) the main sources at Aquilate Mere are from both aerial and hydrological inputs. Three main inflows enter the lake (Figure 1C) which contribute hydrological in-wash of microfossils, particularly from the eastern side of the catchment into the mere combined with numerous agricultural ditches and brooks that drain the surrounding agricultural land and the outflow from at Norbury Junction on the Shropshire Union canal (Pittam, Foster, and Mighall 2009). Numerous studies suggest that streams contribute a substantial amount of pollen (e.g. Bonny 1978; Brown, Carpenter, and Walling 2007), possibly accounting for between 85 and 93% of the preserved record (Pennington 1979) and 92% in a study by Qinghai Xu et al. (2012). Additional sources of pollen include aerial deposition from local and extra local sources (cf. Bonny and Allen 1984; Jacobson and Bradshaw 1981) and a regional component from airborne pollen. The mere is presently surrounded by managed

parkland dominated by grassland, isolated mature oak stands and early nineteenth century AD plantations (Figure 1C; Yale 1994). Isolated coniferous plantations also grow in the catchment. Other land use categories include pasture with small areas of arable agriculture. The local solid geology is Permian-Triassic Old Red Sandstone (Ambrose et al. 2020). This underlies coarse-grained superficial deposits largely in the form of outwash gravels and eskers that were deposited during the Devensian glaciation (Glasser 2003, 2004). The catchment soils are very diverse with nine soil associations recorded.

Material and Methods

A 5 m core was recovered from AQM using a combination of a 150 × 5 cm Mackereth Corer and a 50 × 5 cm Russian corer (Aaby and Digerfeldt 1986). The Mackereth core was extruded in the laboratory at 1 cm intervals using a slicing plate. The Russian cores were transported intact from the field in plastic tubing wrapped in polyethylene. The sediment was stored at 4°C prior to sub-sampling.

Chronology

A chronology for the core was obtained using a combination of radiometric analyses (¹⁴C, ¹³⁷Cs, ²¹⁰Pb) and Spheroidal Carbonaceous Particles (SCPs), each procedure following routine protocols. Two bulk sediment samples from 475–477 cm and 245–247 cm depth respectively were submitted to Beta Analytic for conventional radiocarbon dating. Dates were calibrated using CALIB 8.20 calibration programme and IntCal20 (Stuiver and Reimer 1993; Reimer, Baillie, and Bard 2009).

To bridge the gap between ²¹⁰Pb and ¹⁴C dating, SCPs were counted to date recent lake sediments from c. AD 1850 (Rose et al. 1995; Shotbolt, Hutchinson, and Thomas 2001; Vukic and Appleby 2005). The extraction of SCPs followed the method outlined by Rose et al. (1995), and 5% of the final residue was mounted onto fixed microscope slides using Naphrax mountant. The total number of SCPs on each slide were counted and then converted to units of particles per cm³ (Rose et al. 1995).

The samples for ¹³⁷Cs and ²¹⁰Pb analyses were packed into pre-weighed PTFE sample holders and lightly compressed to provide a sample depth of 40 mm (to match the geometry of the active Ge volume in the well detectors used for analysis; Appleby et al. 1986). After reweighing, the sample holders were sealed using Subaseals® and paraffin wax to prevent ²²²Rn gas escape. All sealed sample holders were then stored for a minimum of 21 days to allow for equilibration of ²²²Rn with the parent isotope ²²⁶Ra. Radionuclide analyses were

undertaken using calibrated Hyper-Pure Germanium Well Detectors with count times of typically between 36 and 96 hours. The seven radionuclides measured are described in Pittam, Foster, and Mighall (2009) and further detailed explanations of the methodology and calibration methods are given by Appleby and Oldfield (1978), Foster et al. (2006) and Walling and Foster (2016).

Microfossils

Sub-samples of 0.5–1 cm thickness were prepared for pollen, non-pollen palynomorph (NPPs) and microscopic charcoal analysis (Barber 1976). After chemical treatment the residue was mounted in silicone oil for counting. At least 500 land pollen grains were counted for each sub-sample except when pollen preservation was poor, or content was sparse, resulting in a lower pollen sum being accepted in some cases. Pollen was identified with the aid of keys (Fægri, Kaland, and Krzywinski 1989; Moore, Webb, and Collinson 1991) and modern reference material. The pollen diagrams were drawn using *Tilia* and *Tilia.graph* version 2.0.b4 (Grimm 1991–1993). Taxa are presented as percentages of total land pollen (TLP), excluding spores and aquatics. As *Myrica* and *Corylus* are difficult to separate (Edwards 1981), these taxa have been combined as *Corylus avellana*-type. Cereal-type pollen are classified as grains greater than 37 μm and with an annulus diameter of more than 8 μm (Moore, Webb, and Collinson 1991; Andersen 1979; Beug 2004). It should be acknowledged that some wild grasses can be incorporated into this group (Tweddle et al. 2005). NPPs were counted during routine pollen analysis and identified using the type system devised by van Geel (e.g. van Geel 1978; 2005) and are expressed as a percentage of TLP and NPPs. Plant nomenclature follows Stace (1997) and takes into account the problems of categorising plant species on the basis of their pollen morphology (Bennett, Whittington, and Edwards 1994). Summary curves for trees, shrubs (constituting arboreal pollen, AP), dwarf shrubs and herbs (non-arboreal pollen, NAP) are shown. Microscopic charcoal was recorded using Clark's (1982) point count method. Zonation of the pollen diagram was undertaken using CONISS (Grimm 1987).

Diatoms were prepared for counting using a H_2O_2 digestion (Renberg 1990) before being air dried and mounted in Naphrax. Samples were counted until a minimum number of 300 diatoms had been achieved for each sample. Taxa are expressed as percentages of the total diatom assemblage (TDA). Identifications were made with the aid of Krammer and Lange-Bertalot (1986; 1988; 1991a, 1991b) and Hartley et al. (1996). Where possible species are classified by their ecological affinities following Denys (1991) and van Dam, Mertens, and Sinkeldam (1994). Zonation of

the diatom diagram was undertaken using CONISS (Grimm 1987). Diatom preservation was poor in the uppermost 130 cm and were deemed unviable for counting. Samples were analysed every 5 cm between 130 and 490 cm.

Geochemistry

Major and minor elements (Si, Al, Fe, Ti, Ca, Mg, P), trace lithogenic elements (Rb, Sr, Y and Zr), and trace metals (Cu, Mn, Pb, Zn) were determined. Sub-samples were digested in a CEM Mars 5 microwave in a 4:1 solution of concentrated HNO_3 and H_2O_2 . Once cooled, samples were filtered, 3 ml LaCl added, and the sample volume made up to 50 ml with deionised water. Analysis was undertaken in either a Unicam 939 Flame Atomic Absorption Spectrometer (for Pb, Cu and Zn) or by Inductively Coupled Plasma-Atomic Emission Spectrometer using the Perkin Elmer Plasma 400 (for other elements). Digestion of certified reference materials using this procedure showed that extraction efficiencies lay between 93 and 98%; the results reported in this paper have not been corrected for recovery efficiency. Quality controls included the use of replicates and spiked standards, and analytical accuracy was $\pm 3\%$. Results are expressed on a mass-specific basis as either mg g^{-1} or $\mu\text{g g}^{-1}$, depending on the concentration range.

Pb enrichment factors (Pb-EFs) were calculated using Zr as a conservative element using the equation $\text{Pb-EFs} = (\text{Pb}_{\text{sample}}/\text{Ref}_{\text{sample}})/(\text{Pb}_{\text{background}}/\text{Ref}_{\text{background}})$ (Boës et al. 2011). Average upper continental crust concentrations were used for the background ratio as site-specific values derived from deeper pre-pollution sediments levels were unavailable. An upper continental crust value of 193 mg kg^{-1} for Zr, was used (Rudnick and Gao 2003). EFs are taken as indicative of relative changes in Pb content, as we are aware that the indiscriminate use of EFs has been previously criticised (Reimann and de Caritat 2000; Kylander et al. 2006; Bern, Walton-Day, and Naftz 2019). In the case of AQM sediments, the use of Zr as reference element for Pb is supported by the PCA results (see below).

LOI

To examine fluctuations in organic carbon, loss-on-ignition (LOI) analysis was conducted on the sediments between 20 and 210 cm, at 2 cm intervals, following the conventional method outlined in Heiri, Lotter, and Lemcke (2001).

Environmental Magnetism

There are several factors that can influence the magnetic properties of lake sediments, such as: the

Table 1. Stratigraphy of Aqualate Mere following Troels-Smith's (1955) classification.

Depth (cm)	Sediment unit	Troels-Smith formula
0–100	Clay	As ₄ ; Nig 3, Strf 1, Sicc 1.5
100–126	Light grey organic gyttja, slight banding.	Dh ^{3.5} ₄ ; Nig. 2.0, Strf. 1.5, Sicc. 2.0
126–220	Dark grey organic gyttja	Dh ³ ₄ ; Nig. 3.0, Strf. 0.5, Sicc. 2.5
220–490	Dark grey gyttja with light grey banding	Dh ^{3.5} ₄ ; Nig. 3.0, Strf. 2.0, Sicc. 2.5

contribution of eroded soil that externally reflects the magnetic signatures of the soil associations being eroded; the fallout of magnetically enhanced atmospheric pollutants; and the possible post-depositional diagenesis of magnetic minerals, or the formation of new minerals such as authigenic greigite (Walden, Oldfield, and Smith 1999; Walling and Foster 2016). Internal lake processes can also alter the magnetic properties of the lake sediment so that they are dominated by these internal processes rather than those reflecting contributions from external catchment or atmospheric sources. The presence of authigenic greigite, for example, can be detected using the ratio of SIRM against χ_{lf} with values exceeding $\sim 20 \text{ kA m}^{-1}$ being indicative of sediments with a greigite signature. A ratio of SIRM to X_{lf} greater than 2 suggests that magnetic signatures may be overprinted by the presence of bacterial magnetite.

A combination of magnetic susceptibility and remanence parameters were measured and/or derived as part of the analysis of the AQM sediments. Mass-specific magnetic susceptibility and remanence characteristics (Supplementary Table 1) were determined on ~ 5 – 10 ml sub-samples of oven-dried (40°C) sediment sieved to $<63 \mu\text{m}$ and in all cases corrected for loss-on-ignition at 550°C (Foster et al. 1998; Walling and Foster 2016). Results are reported on a minerogenic basis because organic matter is usually diamagnetic and dilutes the magnetic signature. Low and high-frequency magnetic susceptibility were measured using a Bartington® MS2 susceptibility meter with an MS2B dual frequency sensor (Dearing 1999). Anhyseretic (ARM) and Isothermal (IRM) remanences were measured using a Molspin® rotating magnetometer. ARM was grown with a DC bias field of $40 \mu\text{T}$ and a peak alternating field of 100 mT in a Molspin a.f. demagnetiser. The ARM values quoted are given as susceptibility of ARM (X_{arm}) and have been normalised to the strength of the DC field. IRMs were grown in a Molspin pulse magnetiser to a maximum field strength of 880 mT which is probably sufficient to saturate the sample (see Walden, Oldfield, and Smith 1999). Measurement of loss of IRM after 24 h (IRM_{loss}) was taken after samples had been magnetised at the

maximum field strength (880 mT). Loss of remanence over time, like frequency dependent susceptibility, is often a function of fine 'viscous' grains on the transition from stable single domain to superparamagnetic (Higgitt, Oldfield, and Appleby 1991). Units of measurement and ratio definitions are given in Supplementary Table 1. A more detailed explanation of magnetic measurements and their interpretation is given by Walling and Foster (2016).

Statistical Analysis

Multivariate statistics were used to summarise common patterns of variation within datasets and to gain insights into the underlying environmental factors that control these. Principal Component Analysis (PCA) was applied to the element composition data in correlation mode and by applying a varimax rotation, using SPSS 20. As these are closed data (Aitchinson, Barceló-Vidal, and Pawlowsky-Glahn 2002; Baxter et al. 2008), a centred log ratio transformation (Aitchinson 2003; Baxter and Freestone 2006) and standardisation (Eriksson et al. 1999) were applied prior to the statistical tests.

Results

Stratigraphy

The stratigraphy (Table 1) is a broadly homogenous, organic-rich gyttja. At a depth of approximately 1 m , the gyttja is overlain by a unit of clay.

Dating

The chronology is limited by only having two radiocarbon dates with 2σ calibrated age ranges spanning up to 400 years. All calibrated ages are expressed in calendar years BC/AD and are rounded up to the nearest half decade based on estimates from the CLAM age-depth model. However, the cited estimated ages in the text must be treated with caution. Notwithstanding this caveat, the 2σ calibrated range of the radiocarbon date positioned close to the base of the

Table 2. Radiocarbon dates from Aqualate Mere (Calibrated using Stuiver, Reimer, and Reimer 2021).

Lab code	Depth (cm)	Conventional ^{14}C age (BP)	2σ Calibrated	Median Probability
Beta-189864	243–247	1530 ± 50	Cal AD 432–638	Cal AD 541
Beta-184151	473–477	2900 ± 70	Cal BC 1367–903	1093 Cal BC

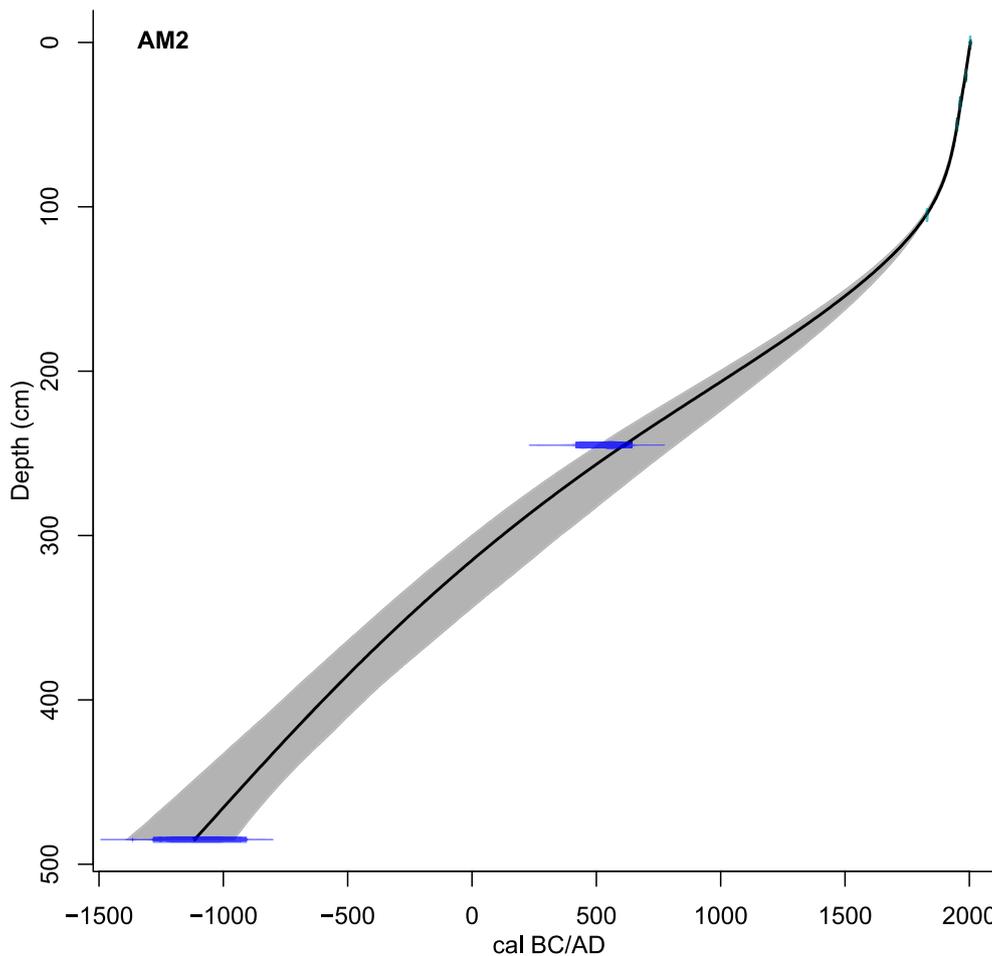


Figure 2. Age-depth model (using a smooth spline) for Aqualate Mere using CLAM (after Blaauw 2010).

core (4.75 m) suggests that the entire sequence covers the last c. 3000 cal. years (Table 2). The initial increase in SCP concentration occurs at a depth of 1.12 m (Pittam, Foster, and Mighall 2009) and is dated to the AD 1830s (e.g. Vukic and Appleby 2005). In contrast to previous studies, when a single major increase in SCP concentrations has been dated to the early AD 1950s (e.g. Rose et al. 1995), two peaks in SCPs occur at 42 and 22 cm depth at AQM. The double peak in the SCP profile has been resolved by supporting dating evidence from the ^{137}Cs profile (see below), which places a depth of 42 cm in the early AD 1950s (see Pittam, Foster, and Mighall 2009). The ^{137}Cs profile demonstrates an initial increase in ^{137}Cs activity up-core from a depth of ca. 60 cm, although the long tail of low ^{137}Cs activities below 50 cm depth may be due to post-depositional diffusion through the profile (cf. Foster et al. 2006). The increase at 50 cm and peak at 37 cm depth most likely correspond to the initiation of atmospheric weapons fallout in AD 1954 and the AD 1963 fallout peak from atmospheric weapons testing respectively. A further peak, at 20 cm depth, was probably caused by fallout from the Chernobyl nuclear accident in AD 1986. The ^{210}Pb chronology placed the sediment at 58 cm as dating to the beginning of the twentieth century, thus

providing a chronological marker that lies between the initial increase in SCP concentrations and the ^{137}Cs profile. The independent chronological markers provided by the ^{137}Cs data appear to match the ^{210}Pb dating very closely. The chronology is also supported by the Pb data presented below. The CLAM software package (Blaauw 2010) was used to create an age-depth model (Figure 2), which combines ^{14}C , SCP, $^{210}\text{Pb}_{\text{un}}$ and ^{137}Cs dates, to infer approximate ages for all layers.

Microfossils

A summary of the major changes in the pollen, spores and selected non-pollen palynomorph record are described in Table 3 that represent various land uses (cf. Brown, Carpenter, and Walling 2007). The record (Figure 3A–C) shows that the AQM catchment contained mixed woodland. Most of the major changes observed in the tree and shrub pollen record involved *Quercus*, *Alnus*, *Betula* and *Corylus avellana*-type (Figure 3A).

Agricultural indicators occur throughout the record. Poaceae is abundant with an increase in values in the upper third of AM6. Cereal-type pollen is more evident from the upper part of zone AM2 as both *Secale cereale* and *Triticum*-type remain at higher

Table 3. Pollen zone descriptions for Aqualate Mere.

Zone	Depth (cm)	Estimated Age (AD/BC)	Description
AM1	490–448	c.1300–895 BC	Increasing arboreal pollen percentages characterised by <i>Alnus</i> , <i>Betula</i> , <i>Quercus</i> and <i>Corylus avellana</i> -type. Poaceae and cereal-type pollen well represented, Prominent Ranunculaceae, <i>Rumex acetosa</i> , <i>Rumex acetosella</i> , <i>Plantago lanceolata</i> and <i>Cirsium</i> type. Minor <i>Anabaena</i> .
AM2	448–395	c. 895–570 BC	High total arboreal pollen percentages, dominated by <i>Alnus</i> , <i>Betula</i> , <i>Quercus</i> and <i>Corylus avellana</i> -type; Initial decline of herbaceous pollen. Cereals and other NAP taxa recover by the end of the LPAZ.
AM3	395–365	c. 570–370 BC	Total arboreal pollen percentages dominate. <i>Rumex acetosella</i> , <i>Plantago lanceolata</i> and <i>Cirsium</i> type more prominent. Cereal-type pollen consistently recorded. <i>Sordaria</i> -type peaks mid-LPAZ. <i>Anabaena</i> well represented.
AM4	365–268	c. 370 BC-AD 390	Gradual decrease in total arboreal pollen percentages; Poaceae and Cereal-type pollen gradually increase; Prominent Ranunculaceae, <i>Rumex acetosa</i> , <i>Rumex acetosella</i> . Increase in degraded, corroded and broken pollen. Sharp rise in <i>Anabaena</i>
AM5	268–251	c. AD 390–550	A slight dip in total arboreal pollen percentages; Poaceae declines; Cereal-type pollen consistently recorded; Prominent Ranunculaceae, <i>Rumex acetosa</i> , <i>Rumex acetosella</i> , <i>Plantago lanceolata</i> , <i>Cirsium</i> type and a peak in <i>Plantago major</i> and <i>Centaurea</i> -type. Sharp rise in <i>Anabaena</i> .
AM6	251–142	c. AD 550–1600	Total arboreal pollen percentages fall in mid-LPAZ. Simultaneous increase in Poaceae and other NAP taxa. Cereal-type pollen percentages decline slightly. A series of sharp, short-lived peaks in <i>Anabaena</i> .
AM7	142–92	c. AD1600–1874	Total arboreal pollen percentages recover; <i>Fagus</i> , <i>Pinus</i> and <i>Picea</i> represented; Herbs well represented; Poaceae, Ranunculaceae, <i>Rumex acetosella</i> , <i>Plantago lanceolata</i> , <i>Plantago major</i> . Cereal-type pollen decreases mid-LPAZ. <i>Anabaena</i> fades.
AM8	92–0	c. AD 1874–2004	Total arboreal and non-arboreal pollen percentages remain fairly stable; <i>Fagus</i> , <i>Pinus</i> and <i>Picea</i> represented, Cereal-type, <i>Plantago lanceolata</i> , <i>Plantago major</i> , coprophilous fungi fade.

values until they fade in zone AM8 (Figure 3B). Each phase of lower tree and shrub pollen is inversely related to increases in non-arboreal pollen and spores with pastoral and disturbance/ruderal affinities (Behre 1981; Brown, Carpenter, and Walling 2007). Coprophilous fungal spores are also consistently recorded throughout the pollen diagram until zone AM8. The erosion-indicator *Glomus cf. fasciculatum* (HdV-207) (van Geel 2001) and *Valsaria cf. variospora* (HdV-140) occur in trace amounts whilst the cyanobacterium, *Anabaena* sp. (HdV-601; van Geel et al. 1994), is well represented in zones AM3-7. Other land uses include wet grasslands/meadows suggested by the presence of Cyperaceae, Apiaceae, *Filipendula*, Ranunculaceae, Rubiaceae, *Urtica*-type, *Sphagnum* and *Equisetum* (Behre 1981; Brown, Carpenter, and Walling 2007). Aquatic and shoreline taxa, likely to be present in or around the mere fringe, include *Nuphar*, *Nymphaea*, *Myriophyllum*, *Potamogeton*, *Sparganium emersum*-type and *Typha latifolia*. *Isoetes* occurs less frequently (Figure 3C).

The diatom record can be divided into five separate assemblage zones (Figure 4). Broadly, these zones correspond to variations in the relative contributions of planktonic/tychoplanktonic, epontic and benthic taxa. AMD-1 is characterised by a planktonic/tychoplanktonic taxa (c. 60% of the total diatom assemblage [TDA]). The diversity of diatoms in this zone is rather limited with *Cyclostephanos dubius*, *Cyclostephanos costalimbus* and *Fragilaria construens* comprising around 70% TDA. *C. dubius* expands to between 4 and 55% in AMD-2 heralding a sharp increase in planktonic taxa to 55–65%. The diversity of planktonic forms also increases with a gradual rise in *Cyclotella radiososa*, *Stephanodiscus rotula* and *Cyclotella bodanica var. affinis*. These patterns continue into AMD-3 with planktonic and tychoplanktonic taxa comprising >70% TDA throughout the zone, despite a gradual

decline in *C. dubius*. AMD-4 marked a significant shift in the lake ecology as the contribution of plankton and tychoplankton falls to between 40 and 50%. Coupled with this development is a sharp decrease in *C. dubius*, the gradual decline in taxa such as *C. costalimbus*, *S. rotula* and *C. bodanica var. affinis* and the emergence of the species *Cyclotella ocellata* and *Navicula scuttelloides*. The emergence of these two species is short-lived and by the beginning of AMD-5 planktonic and tychoplanktonic species dominate the assemblage once again. Nevertheless, the assemblage is somewhat different to previous zones with *F. construens* dominant and *Cocconeis placentula* subdominant.

Throughout the analysed section the diatom flora is dominated by species ($\geq 80\%$ TDA) with a preference for mesotrophic to eutrophic conditions. At the opening of the analysed sequence (AMD-1) these types are relatively evenly balanced. Into zones AMD-2 and AMD-3 eutrophic forms represent approximately 55–70% TDA. By AMD-4 and AMD-5 there is a decline in eutrophic diatoms and an expansion of mesotrophic to eutrophic taxa.

Geochemistry

Five Principal Components accounted for 84% of the total variance of the chemical composition of the samples (Figure 5; Supplementary Figure 1; Supplementary Table 2): Cp1 has large positive (>0.7) loadings of Fe, Si, and Mg, moderate-low (0.38) positive loading of Mn, large negative (<-0.7) loadings of Al and Rb, and moderate-low negative loadings of Zr (-0.53) and Y (-0.32). Cp1 reflects two contrasting mineralogies, since the elements with negative loadings usually occur in larger concentrations in felsic minerals (like K-feldspars) and those with positive loadings tend to be enriched (except for Si) in mafic

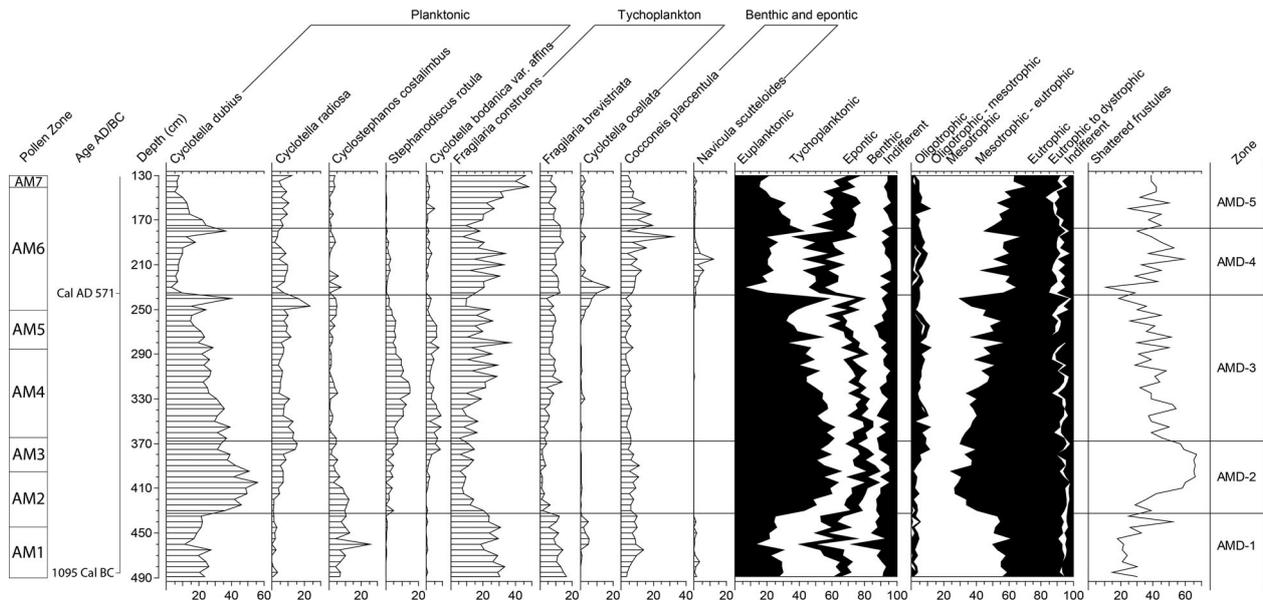


Figure 4. Percentage diatom diagram by depth.

until c. AD 300 (in two phases: from c. 300 BC to c. 100 BC, and AD 100–300). An isolated peak occurs at c. AD 1070, another phase of elevated scores between c. AD 1380 to c. 1600, a peak by c. AD 1690, low values until the end of the nineteenth century and a moderate increase during the twentieth century. The pattern broadly resembles that shown by the magnetic susceptibility (Pittam, Foster, and Mighall 2009), which is interpreted as reflecting catchment sources with little influence from internal lake processes.

Cp2 has large positive loadings of LOI (i.e. organic matter; also see Figure 6A) and biophilic elements (P and Mn), and large to moderate negative loadings of Pb and Zr. Although values are low, it is also significant that Si, Rb, Al, which are hosted in the mineral phase, have negative loadings and Ca, which is a biophilic element, has a positive loading on this component. Thus, Cp2 mainly reflects the content of organic versus mineral matter in the sediments and most likely reflects within lake bio-productivity. Most of the P seems to be in organic form, as suggested by this component, and thus it does not reflect fluxes from the catchment.

Cp3 is characterised by large positive loadings of Zn and Y, and a large negative loading of Ti (Figure 5). Zn may derive from material from the canal located at Norbury Junction in the top metre of the core (Pittam, Foster, and Mighall 2009). Thus, this part of this component may be related to fluxes from the canal. This is supported by the abrupt increase in Cp3 scores since the mid-twentieth century. Even though the canal has not made a significant contribution to the sediments accumulated in AQM during the last 45 years (Pittam, Foster, and Mighall 2009), it does not mean that the flux cannot be detected. Relatively high positive scores were found in samples with ages between

c. 860 and c. 610 cal. BC which are too old to relate them to the canal and therefore must originate from another source (or sources) with a similar chemical composition.

Cp4 is characterised by large positive loadings of Sr and Cu, and a moderate-low negative loading of Mg. This might relate to different soil sources from the catchment. The scores show elevated values for samples with ages older than c. 900 cal. BC, decreasing values by c. 850 cal. BC, almost constant values (around zero) until the beginning of the twelfth century, elevated values until mid-seventeenth century and a rapid decline after that (Figure 5).

Cp5 is characterised by a large positive loading of Ca, and moderate-low negative loadings of Zr and Mg. The most evident change in the record of scores occurs at the beginning of the sixteenth century, when concentrations (mainly Ca) start to increase, accelerating by the beginning of the twentieth century. Increase Ca loadings may reflect lake eutrophication, but the opposite can happen (see Murphy, Hall, and Yesaki 1983). Bio-productivity (Cp2) does not follow the increase in Ca fluxes in the upper part of the core, possibly because climatic conditions may have depressed it during the Little Ice Age.

Four major phases of Pb enrichment are recorded in the AQM core (Figure 5). The PbEF record shows relatively high values: (i) during the Bronze Age through to the transition to the Early Iron Age; (ii) enrichment during the Late Iron Age and the Roman period (with a similar record to Cp1); (iii) a sharp increase during the mid-5th AD, before gradually declining through to the mid-14th AD; (iv) towards the top of the core, where an increase occurs in three steps: the first from the 14th to mid-seventeenth century, the second from the mid-

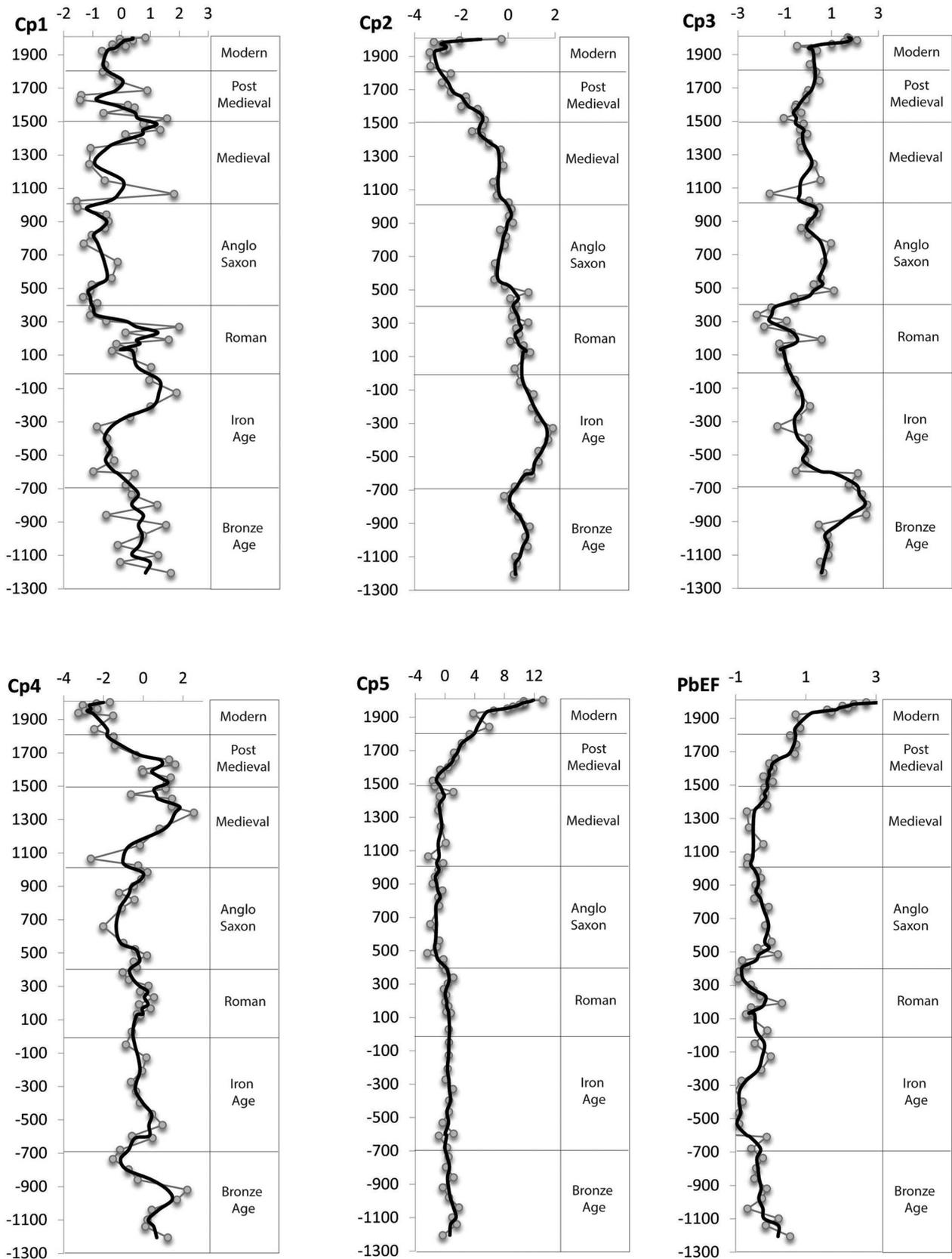


Figure 5. Principal Component Factor Scores (Cp1–Cp5) and Lead (Pb) enrichment values by age for Aqualate Mere. The zones for the pollen and diatoms are shown to facilitate comparisons and main archaeological periods.

seventeenth century to the beginning of the twentieth century, and the third and most dramatic one since then. Despite the decrease in Pb concentrations (Supplementary Figure 1), the PbEF do not imply lower atmospheric metal pollution. Martínez

Cortizas et al. (2012) found a similar situation, probably due to a coal-fired power station (operational in the recent past) replacing other sources of Pb pollution. This may also apply to AQM with the coal-fired power station of Coalbrookdale (approximately

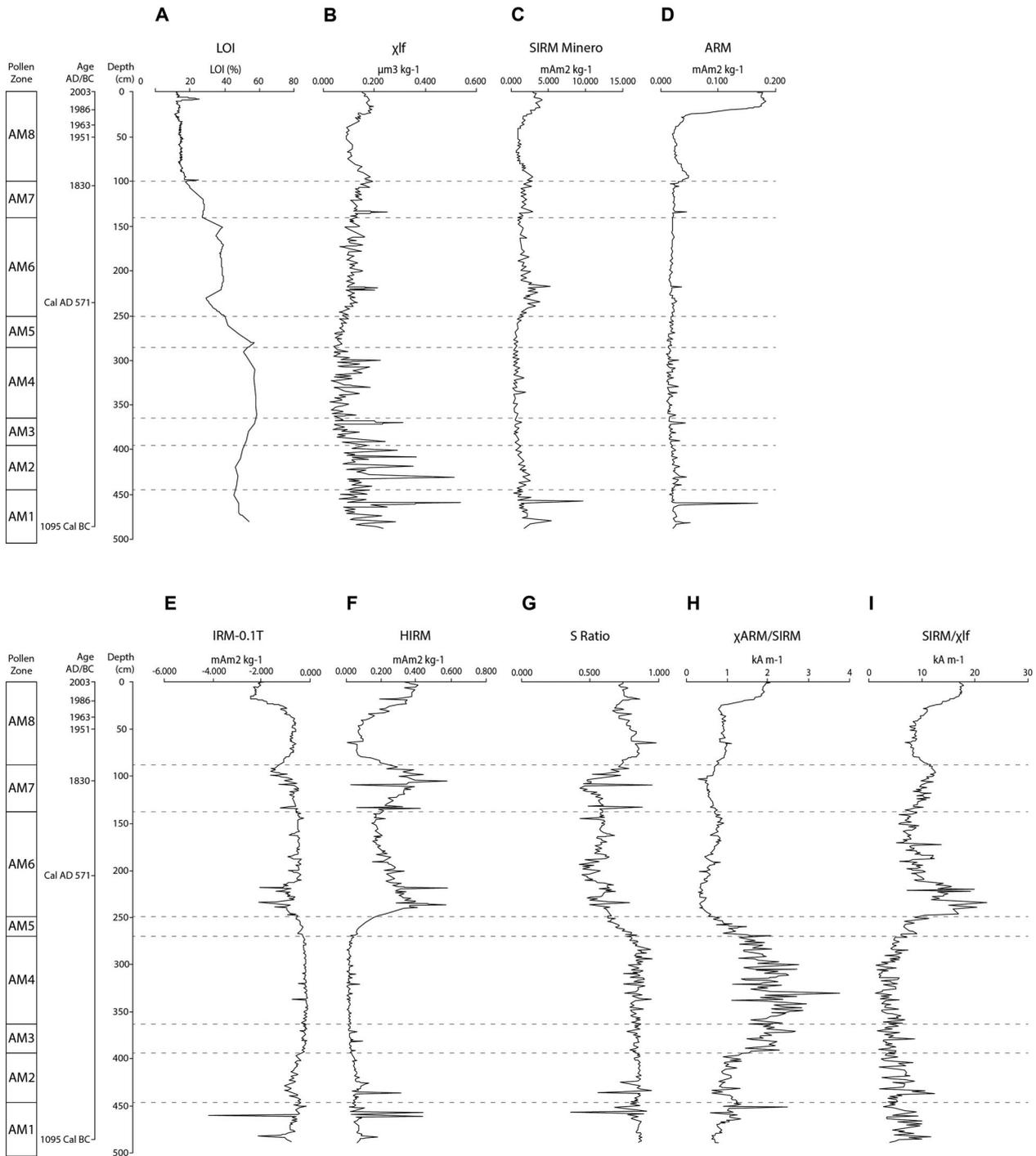


Figure 6. Environmental magnetism measurements by depth for Aqualate Mere.

20 km to the south-west of Newport) being operational since 1969.

LOI and Environmental Magnetism

There are three major zones reflecting differences in LOI (Figure 6A). From the base of the core to ~250 cm depth when LOI generally exceeds 40%. From 250 cm to 125 cm depth, LOI averages ~30% and upcore of 125 cm depth, LOI is generally less than 20% upcore. Because of the very high LOI values, all magnetic concentrations reported below are corrected for LOI.

Magnetic susceptibility (Figure 6B) is highly variable below 3 m depth in the core and the variability diminishes significantly upcore. The upper 3 m of sediment also shows some minor general trends including slightly higher χ_{lf} values in the upper 30 cm and between 75 and 125 cm depth. The low values below $1 \times 10^{-6} \text{ m}^3 \text{ kg}^{-1}$ suggest that significant quantities of ferrimagnetic minerals are probably not present in these sediments (Dearing 1999).

IRM880mT (Figure 6C) shows broad trends similar to those of χ_{lf} but with significantly less variability below 3 m depth in the core while ARM values

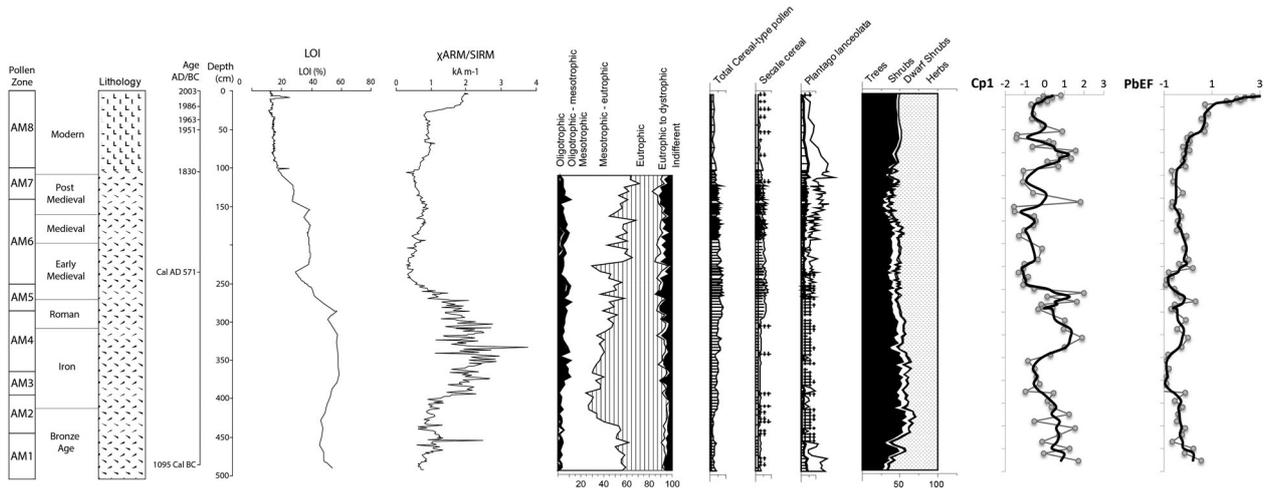


Figure 7. Environmental synthesis of selected proxies showing the key trends including from left to right: Pollen zones based on TLP%; Cultural periods; Lithology; Age, Depth; Loss-on-ignition [LOI], χ ARM/SIRM; Diatoms, Anthropogenic pollen indicators; Ratio of tree, shrub, dwarf shrub and herb pollen; Principal Component Cp1 and Lead (Pb) enrichment.

(Figure 6D) only show a significant increase in the upper ~ 25 cm of the entire sequence. Of note is the trend in the S ratio (Figure 6G) which shows three distinct zones, two with a ‘soft’ remanence with S ratios over 0.8 (0–80 cm depth and below 275 cm depth) and a ‘harder’ remanence with lower S ratios in the central portion of the core. The χ ARM:IRM 880mT ratio (Figure 6H) exceeds 2 between ~ 300 and 375 cm depth and increases towards 2 in the upper 25 cm of the core whilst the SIRM:Xlf ratio (Figure 6I) generally remains below 20.

Discussion

Land Use Changes During the Bronze and Iron Age

There is some known prehistoric archaeology surrounding AQM and recorded across Staffordshire and Shropshire more generally, particularly contemporary material culture, including Bronze Age burnt mounds and cremation cemeteries (Hurst 2011). The AQM pollen record provides evidence for human impact during the mid to late Bronze Age, characterised as short-lived clearances interspersed with periods of woodland recovery (Zones AM1 and 2; c. 1310–700 cal. BC; Figures 3A,B). Even when the arboreal pollen (trees and shrubs) record suggests a period of woodland regeneration, and evidence for human activity diminished, it did not dissipate altogether. Percentages of pastoral and disturbance indicators fall but many are present throughout this time in trace amounts. Arable agriculture also continues, possibly uninterrupted, as cereal-type pollen is recorded. This supports Dark’s (1999) assertion that cultivation was already widespread in Iron Age Britain.

Low arboreal pollen percentages between 490 and 480 cm (c. 1115–1085 cal. BC) and 460 and 450 cm

(c. 965–905 cal. BC) are suggestive of short-lived woodland clearances. Cereal-type pollen, including *Secale cereale* (rye), provides evidence of cultivation while pastoral and disturbance/ruderal indicators and coprophilous fungal spores, that are indicative of grazing, are also regularly recorded (Figure 3B,C; Brown, Carpenter, and Walling 2007; Perrotti and Van Asperen 2019). Finds of *Secale cereale* are rare in the Bronze Age and may be possibly intrusive weeds rather than the result of cultivation (Barclay and Fairweather 1984; Boyd 1986). *Secale cereale* pollen grains do occur from the second millennium BC in British peat and lake sediments and some seeds recovered from LBA contexts mean that it could have been used as a fodder, food grain or other type of crop (Chambers and Jones 1984; Chambers 1989). The percentages of *Secale* found at AQM exceed 1% TLP, a value taken by some as indicative of cultivation, but the criteria for a 1% threshold to differentiate between weed and crop rye is not clearly established (Chambers 1989). Its occurrence at AQM, alongside pollen from *Triticum/Avena*-type (wheat/oats) and *Hordeum*-type (barley) (Figure 3B), does not exclude the possibility that rye was wild amongst those crops. Given the regular presence of rye pollen at AQM extends back into late prehistoric times, the contention that domesticated rye was introduced by the Romans is not supported here. Although the reason for this is unclear, rye seemingly became an important crop at AQM, a feature also recorded in Denmark and the Low Countries during the first millennium AD (Chambers 1989).

The second phase of woodland clearance is coincident with an increase in Cp1 reflecting a change in the source of mineral material entering the mere (Figure 5). The amount of degraded, corroded and broken pollen grains also increases slightly, typical of fluvial transport (cf. Cushing 1967), and LOI values are lower. Although there are no archaeological records

of Bronze Age activity within the immediate vicinity of AQM (Wardle 2003), there is a small cluster of findspots located along the A5 Watling Street to the immediate south and a single round barrow at the source of the River Penk. Evidence of woodland clearance and agriculture is also shown in the pollen record at King's Pool in Stafford (Bartley and Morgan 1990). Rowley (1971, 31) has suggested 'lowland settlement during the Bronze and Iron Ages was far more important than had previously been thought', and the AQM microfossil record lends some support to this assertion.

Woodland regeneration occurred during the Bronze Age throughout Staffordshire and Shropshire as a response to reduced human activity although the nature of the regeneration differs from site to site (e.g. Beales 1980; Twigger 1988). At AQM it occurs between c. 905 and 700 cal. BC (450–414 cm: Figure 3A). This may have been a product of what Darvil (1987, 75) termed 'social discontinuity in the south'. This occurred as far north as the English Midlands manifesting itself as settlement abandonment, woodland regeneration (e.g. Dark 2006) and the development of scrub grassland (e.g. Sims 1978). Woodland recovery occurred at AQM and the pollen evidence suggests that while human activity diminished, especially midway through zone AM1 and during the first half of zone AM2 (Figures 3A,B), agriculture appears to have continued. Woodland regeneration, a concordant decline in cereal production and possible land abandonment, especially in the British uplands, around the time of the Bronze Age/Iron Age transition continues to be debated (Amesbury et al. 2008; Davies 2007; Dark 2006; Armit et al. 2014; Stevens and Fuller 2015; Bevan et al. 2017), and a shift to a colder and/or wetter climate (e.g. Barber, Chambers, and Maddy 2003), attributed to a decline in solar activity (van Geel, Buurman, and Waterbolk 1996a), may have been influential. While weaker chronological resolution and plateaux in the radiocarbon calibration curve hampers the precision of palaeoecological records at AQM at this time, the age-depth model suggests that the '850 cal. BC climatic shift' may have been coincident with the phase of woodland regeneration based on an increase in arboreal pollen (c. 440–441 cm, Figure 3a). Any increase in the soil moisture content at AQM would have also encouraged carr woodland and waterlogging by raised groundwater levels in low lying areas of the catchment (cf. Yates 1999; Macklin, Johnstone, and Lewin 2005; van Geel, Buurman, and Waterbolk 1996a) which could have in part facilitated a downturn in agricultural activity surrounding AQM. More pragmatically, Twigger (1988, 751) proposes that the reduction in agricultural indicators is due to the 'shift in farming activity away from land close to the meres'. Irrespective of the cause of any downturn, soil erosion continues in the AQM catchment based on the magnetic

measurements and geochemistry: several short-lived 'spikes' in χ_{lf} , SIRM_{minero} and ARM, IRM – 0.1 T, HIRM and the S ratio (Pittam, Foster, and Mighall 2009; Figure 6), and an increase in the concentration of, or a short-lived peak in, lithogenic elements (Cp1, dip in Cp2 and peak in Cp3 scores (Figure 5) largely driven by increases in Zr, Y, Al, and subsequently Si and Ti; Supplementary Figure 1).

The diatom flora indicates a major shift to eutrophic conditions occurs at c. 790 cal. BC (Figures 4; 430 cm and 7). *Cyclostephanos dubius* and *Stephanodiscus rotula* values increase, followed by *Cyclotella radiosa*. Abundant *Cyclostephanos dubius* has been often used to infer eutrophic conditions in lakes (e.g. Gaillard et al. 1991) although this association is not always observed (e.g. Sayer 2001). Whilst indicative of eutrophic conditions, the abundance of *C. dubius* may be due to a mixing regime in the relatively shallow AQM that favours its growth as well as light availability, nutrient recycling and biotic interactions (Bradshaw and Anderson 2003). The reason for the sudden shift to more eutrophic conditions is not clear but it does occur after the phase of Bronze Age cultivation and before the major increase in cereal pollen. The diatom shift also lags an increase in P concentrations, thus the pattern may indicate a delayed response to increased nutrient loading into the mere (Figure 4). Nutrient inwashing associated with eutrophication has been observed in English lake sediment records from the Bronze Age onwards (e.g. Fritz 1989; Bartley and Morgan 1990). However, total P concentrations may not be a reliable indicator of past nutrient loading (Smol 2002). Cp2 (Figure 5) suggests that most of the P in the sediments of Aqualate Mere is in an organic form and therefore not necessarily reflecting past P loads but P fixation by within lake bio-productivity.

The transition between the Late Bronze Age and Early Iron Age is not clearly defined in the west Midlands of England, partly due to the difficulties with the radiocarbon calibration curve between 800 and 400 BC (Hurst 2011). Phases of woodland clearance interrupted by regeneration continued in the later prehistoric period surrounding AQM, but the local landscape remains well wooded based on the relatively high arboreal pollen percentages until the present day as shown by the extent of woodland around the mere today (Figure 1C). A disturbance phase occurs in the upper part of zone AM2 and into AM3 c. 660–535 cal. BC (from c. 410 cm: Figure 3A,B). The decline in mainly *Betula*, *Alnus* and *Corylus-avellana*-type pollen coincides with a period of agricultural intensification as cereal-type pollen increases rapidly to 5–6% TLP (Figure 3B) and coincides with a shift in the Cp 1 scores (Figure 5). Scores shift from negative to positive values, suggesting the variation of fluxes from parts of the catchment with a more felsic to more mafic mineralogy. Pastoral pollen

indicators also increase, and coprophilous fungi are consistently recorded. A small spike in *Anabaena* sp. also was recorded at c. 535 cal. BC (390 cm; Figure 3C), which may indicate increased nutrient loading derived from agricultural activities and/or from weathering of P-rich bedrock. van Geel et al. (1994; 1996b) suggested that intensification of farming and land fertilisation had a similar effect on the trophic conditions of Lake Gosciadz in Poland. The increased occurrence of *Valsaria variospora* (HdV-140) is also indicative of wet, eutrophic conditions (van Geel et al. 2003). Increased P concentrations commence from approximately c. 850 cal. BC (441 cm; Supplementary Figure 1) until 200 cal. BC (342 cm). However, there is a lag between the rise in P and increased *Anabaena* sp. *Cyclostephanos dubius* and *Cyclotella radiososa* are also well represented, and *Stephanodiscus rotula* increases in value (Figure 4). This strongly suggests that arable agriculture is possibly driving nutrient enrichment as pastoral and disturbance indicators including coprophilous fungi are more subdued except for *Rumex acetosella* at this time (Figure 3B).

Evidence for bacterial magnetosomes is shown in the downcore variations in the $\chi_{\text{arm}}:\text{SIRM}$ ratio (between 370 and 300 cm; 400 cal. BC – cal. AD 120) with the occasional spike to 250 cm (cal. AD 560; Figures 6H and 7). Oldfield, Appleby, and Van der Post (1999) used this ratio to detect the presence of bacterial magnetosomes: ratios must exceed $2 \times 10^3 \text{ A m}^{-1}$ to be strongly indicative of their presence. Although they are not considered to be a major influence on magnetic signatures for most of the mere sediment record, especially in the upper 1.3 m, their presence at this time also points to strong enough eutrophic conditions to promote their formation.

While archaeological remains (such as hillforts, burial sites, pottery and metalwork finds) are more abundant to the west and south, the intensively farmed landscape at AQM seems typical of the English midlands during the Iron Age (Hurst 2011) and commensurate with evidence of enclosures and lowland farmsteads that have been discovered elsewhere in Staffordshire (e.g. Smith 1979). Evidence for agricultural activity and woodland disturbance at AQM is also consistent with changes taking place elsewhere in the region. Extensive clearance occurred on the terraces of the lower Severn valley and floodplain of the Avon valley in Warwickshire and Worcestershire by the MBA and during the Iron Age (Brown 1982; Brown and Barber 1985). At Fenemere and Baschurch Pool, Shropshire, Twigger and Haslam (1991; 749) state that ‘the small-scale clearance and regeneration [...] gave way to more widespread woodland clearance at 800 BC’ which may tentatively indicate the expansion of human activity. The pollen record from Featherbed Moss in Derbyshire shows woodland clearance from the Iron Age with open land from at least c. 170 cal.

BC to c. cal. AD 90 (Tallis and Switsur 1973) and at a nearby site to AQM, Crose Mere, Shropshire, Beales (1980) shows much of the woodland was cleared by the early Bronze Age, with regeneration occurring during the early Iron Age before renewed clearance in the latter stages of the Iron Age peaking between c. 360 cal. BC to cal. AD 80.

Another phase of woodland clearance at AQM took place c. 200 cal. BC (c. 341 cm; zone AM4; Figure 3A). The later Iron Age marked a time of further agricultural intensification at AQM. Increased cereal-type pollen is recorded c. 190 cal. BC. The proportion of degraded, broken, and corroded pollen is indicative of increased deposition of secondary, reworked pollen (Figure 3A) and increasing lithogenic elements (suggested by a peak in Cp1; Figure 5) indicate that agricultural activities were intense enough for soil erosion (cf. Silva-Sánchez et al. 2014) but Rb, Al and Ti all decline (Supplementary Figure 1). The variation in the response of the lithogenic elements here and elsewhere in the sequence probably reflects the varied nature of both the bedrock and the catchment soils (cf. Martínez-Cortizas et al. 2005) and the data here warn against over-reliance of using one or two lithogenic elements as a proxy for soil erosion (e.g. Hölzer and Hölzer 1998; Lomas-Clarke and Barber 2020). Despite this activity the diatoms suggest that the mere became more mesotrophic: *Cyclostephanos dubius* and *Cyclotella radiososa* decrease (although *Stephanodiscus rotula* increases) and by 310 cm (c. cal. AD 40; Figure 4) *S. rotula* decline as *Fragilaria constrens* and *F. brevisstrata* increase. P concentrations also decline.

Roman Period

Following a brief period of woodland regeneration starting at c.115 cal. BC (330 cm; Figures 3A and 7), also seen at Crose Mere and Baschurch Pools (Beales 1980; Barber and Twigger 1987) but not at Stafford (Bartley and Morgan 1990) at this time, renewed clearance commenced c. AD 160 and 525 at AQM (between 298 and 254 cm; Figure 3A) and following a short-lived recovery continued into the early Medieval/Anglo Saxon period (c. AD 755) as the trends described for the end of the Iron Age continue. Evidence for soil erosion persists as the minerogenic content of the mere sediment changes (with an increase in $\text{SIRM}_{\text{minero}}$, HIRM, $\text{SIRM}/\chi_{\text{lf}}$, and $\text{IRM}-0.1 \text{ T}$, and a decrease in the S ratio and $\chi_{\text{ARM}}/\text{SIRM}$ (Figure 6H). These changes coincide with an increase in the mafic dominated material and concentrations of the lithogenic elements (Cp1 and Cp2; Figure 5), particularly Si, Rb, Zr, Y and Al (Supplementary Figure 1). LOI values decreased from 55% at 281 cm to 29% at 231 cm. *Glo-mus cf. fasciculatum* (HdV-207) shows a series of small peaks until c. 240 cm (Figure 3C). Pastoral indicators

are regularly recorded at low values suggesting animal rearing continued alongside cereal cultivation.

Studies conducted in lowland Staffordshire suggest that significant areas of woodland had been cleared before the Romans arrived (e.g. Leah et al. 1998; Ciaraldi 2002; Stevens 2008). As with most areas of Roman Britain, the period is characterised by woodland clearance and crop cultivation (Dark 1999) despite the abandonment of some forts in the county by the early 2nd century AD in Staffordshire but not all e.g. Penkridge and Rocester which lasted until the 4th century AD (Blake, Dean, and Wardle 2018). The main crops grown were spelt wheat (*Triticum spelta*), barley (*Hordeum vulgare*), with bread wheat (*Triticum aestivum*), rye (*Secale cereale*) and oats (*Avena sativa*) and, notwithstanding the difficulty in identifying cereal species in pollen records, cereal pollen is well represented at AQM (Figure 7). Visible cropmark evidence along with extensive enclosures and associated farmsteads or settlements are found across lowland areas in Staffordshire with evidence for both animal rearing and crop cultivation and is compatible with evidence from AQM.

Although the chronology at AQM remains too imprecise to confirm the precise timing of initial Roman impacts (e.g. Dumayne-Peaty and Barber 1997), others (e.g. Dark 2005) have shown that the influx of Roman garrisons into Britain led to woodland clearances to provide agricultural land to supply the expanding migrant population: thus, the period is mostly marked by agricultural intensification and deforestation (Oldfield et al. 2003; Esmonde Cleary 2011). At some sites, such as the landscape close to Crose Mere, remained well-wooded but cereal cultivation appears to have continued locally during Roman times (Beales 1980). At AQM, rye becomes increasingly dominant as woodland clearance, especially a reduction of *Quercus*, continues from c. cal. AD 120 (300 cm, Figures 3B and 7). The continued high cereal pollen values indicate the importance of producing food as the influx of the Roman Army and its retinue, combined with a larger resident population, would have resulted in significant increases in demand. Davill (1987) estimates that the population reached five million in Britain during the first and second century AD as a product of the increased political stability and the formation of a market economy. Even if local demand was satisfied, AQM may also have been within a resource procurement zone to supply and service military garrisons to the west and north of the region (Esmonde Cleary 2011) as most of the newly intensive agricultural systems have been found to be located close to centres of *Vici* and forts. The Sites and Monuments Record (<https://www.staffordshire.gov.uk/environment/Environment-and-countryside/HistoricEnvironment/Overview.aspx>) indicates significant Roman military and domestic presence in

the region with 61 forts built to suppress the native tribes of the *Cornovii*, *Corielsolilii*, *Ordovices* and *Deceangli*, with an additional 236 Roman find spots recorded. Wardle (2003) speculates these could be sites of villas. Glimpses of Romanisation on the agricultural landscape of Staffordshire and Shropshire include extensive field systems and agricultural buildings that were discovered near Wall, Staffordshire.

Early Medieval Period

Typically, the 4th century AD (commencing around 280 cm at AQM) was a period of diminishing Roman influence in England culminating in the withdrawal of the army. As Staffordshire is essentially rural in character, Blake, Dean, and Wardle (2018) suggest that it was largely unaffected by the end of the Roman administration. The impact of the Romans began to decrease in the late third century AD as the removal of large garrisons lowered the population and thus requirements for cereal production. At the same time there was reported widespread disturbance within the countryside; the removal of the political and economic stability of the occupation reduced the structured Roman markets developed to trade surplus goods (Wacher 2001). Thus, it has been suggested that the end of the Romano-British period was characterised by the widespread abandonment of cultivated fields, possibly in the form of woodland regeneration, or the conversion to a stronger pasture-based agricultural system (e.g. Dark 2005). The evidence for this is less forthcoming at AQM as the microfossil data suggests agriculture continued despite a small decrease in total cereal pollen in the uppermost part of zone AM4 (Figure 3B) and lower Cp1 factor scores (Figure 5). Evidence for diminished agricultural activity is not seen in the record from King's Pool, Stafford (Bartley and Morgan 1990), further supporting the idea that parts of Staffordshire were still exploited for agricultural purposes throughout the Iron Age into the post-Roman period (Blake, Dean, and Wardle 2018). Rye, barley and, to a lesser extent, wheat production continued at AQM (Figure 3B). Lower *Quercus* pollen percentages between c. AD 430 (264 cm) and c. AD 760 (230 cm; Figure 3A) are suggestive of the exploitation of oak. Dark (2005) cites dendrochronological evidence for the removal of woodland from across Britain during this period. Slightly increased contributions from *Corylus avellana*-type and *Betula* pollen at AQM suggest that the early post-Roman period was possibly characterised by more secondary woodland but there is no evidence for major woodland clearance, except for *Quercus*. Agriculture appears to drive changes in the lake sediments properties reflected in the magnetic measurements: SIRM_{minero}, HIRM, SIRM/χ_{lf} increased and IRM-0.1 T, S ratio and XARM/SIRM decreased. Cp1

factor scores increase (Figures 5 and 7), suggesting that soil erosion continued. Both cultivation and pasture continued: cereal-type pollen percentages fluctuate between 5 and 7% TLP until 226 cm, c. cal. AD 800 and pastoral and ruderal taxa are also recorded in the AQM pollen diagram (Figure 3B), suggesting that a mixed agrarian economy continued into the Anglo-Saxon period with little evidence of any major disruption (cf. Losco-Bradley and Kinsley 2002).

Agricultural activities continued as the mere became less eutrophic following a short-lived phase between 250 and 240 cm (cal. AD 560–660). *Cyclostephanos dubius* and *Cyclotella radiosa* values decline sharply with *Stephanodiscus rotula* and *Cyclotella bodanica* var. *affinis* values indicative of more mesotrophic to eutrophic conditions (Figures 4 and 7). These changes coincide with a sustained increase in *Fragilaria construens* and a short-lived rise in *Cyclotella ocellata*. *Anabaena* sp. percentages are low as the diatoms indicative of eutrophic conditions return to numbers last seen in the Bronze Age. Other possible factors could explain these trends including grazing by benthic invertebrates which can affect *Cyclostephanos dubius* and *Stephanodiscus* species and/or NO₂ and NO₃ concentrations and light conditions (Bradshaw and Anderson 2003).

Notwithstanding the occasional recovery, a slight downturn in cereal cultivation and some indicators of agriculture in the non-arboreal pollen record occurred from c. AD 800 (226 cm; Figure 3B). This may be due to the reversion to a more subsistence based economy and smaller population. The pollen record sees an increase in *Quercus* and *Pinus* with a slight fall in *Betula* percentages (Figure 3A). A reduction in agriculture probably led to oak regeneration and increased pine. Less minerogenic sediment (falling Cp1 factor scores) entered the lake. However, by the Norman Conquest a sizeable mixed agrarian economy existed: cereal pollen, including rye and wheat, was at approximately 6% TLP at AQM (Figures 3B and 7). The density of plough lands within the county suggests that the area around AQM was intensively cultivated and possibly heavily populated. Assuming the chronology is robust enough to encompass the Norman Conquest, the AQM pollen sequence should be comparable with land use recorded in the Domesday Book (1086 roughly equates to c. 198 cm; Figures 3A–C). There are numerical records of land directly related to Aqualate Mere and its catchment, encompassed in the Cuttle stone Hundred, a major regional subdivision for the survey. Meretown, the nearest administrative unit to the mere itself, is recorded as such:

{In CUTTLESTONE Hundred}

MERE(TOWN). Earl Algar held it. 4 hides, with its dependencies. Land for 10 plough. In lordship 1; 2 slaves;

18 villagers with 10. ploughs,

A mill at 3s; 4000 eels; woodland ½ league long and 2 furlongs wide. Value before 1066 £4; now 10s more

The Domesday Book, translated by Morris (1976)

From this, it can be calculated that Meretown had woodland covering approximately 100,000 m² although Darby and Terret (1971) cast doubt as to the ability to accurately convert Domesday measurements into modern measurements owing to inherent inaccuracy and imprecision in the estimation of land usage within the original document. Although it is difficult to ascertain the location of the woodland within the catchment at the time of the Domesday Survey owing to a lack of information regarding the spatial extent of each of the administrative units, the AQM record supports the Domesday records that substantial amounts of woodland remained in the catchment which lies between the well wooded Staffordshire (32% total land area) and the relatively open county of Shropshire (8%) at the time of the Norman Invasion (Rackham 1986). Increased Poaceae pollen percentages and other taxa indicative of pasture, especially from 190 cm (c. AD 1170), are regularly recorded as are coprophilous fungi (Figure 3B,C) so the role of pasture was integral to the Early Medieval agricultural economy.

The final major decrease in arboreal pollen (trees and shrubs) commenced at c. AD 1265 (180 cm; Figure 3A), halfway through zone AM6 and, notwithstanding the occasional reversal, continued to fall until c. AD 1550 (148 cm), coincident with the AM6/7 zone boundary. The decline in woodland at the time of early Monastic activity appears to be due to felling that occurred during the medieval period in the centuries preceding the Domesday Survey (Hoskins 1975). *Quercus* and *Betula* percentages are most affected from approximately 182 cm to 142 cm (AD 1600; Figure 3A). Rackham (1986; 88) states that woodland was to shrink from a coverage of 15% of England in AD 1086 to perhaps 10% by AD 1350, although documentary records that cover this period are scarce and often fragmentary owing to the unmanaged nature of the woodland removal. Similar impacts are also recorded in pollen diagrams elsewhere in England (e.g. Oldfield et al. 2003). In common with previous phases of woodland clearance, pastoral and disturbance indicators are recorded in increased percentages at AQM and cereal-type pollen is also present. This phase of deforestation and agriculture caused a short-lived shift in the diatoms suggesting an increase in eutrophic conditions seen by increased amounts of *Cyclostephanos dubius* (Figure 4).

Occasional short-lived periods of woodland regeneration occur throughout the gradual decline of woodland in the latter half of zone AM6 (Figure 3A).

These probably represent small fluctuations in agricultural regimes and periods of woodland regeneration caused deliberately and/or naturally possibly exacerbated by changes in climate and possible outbreaks of disease. The Black Death pandemic occurred in Britain between AD 1348 and 1350 and this has been linked to declines in cereal production, the area under pasture, and to reforestation recorded in pollen diagrams with robust chronologies (decadal-scale precision) and high palynological resolution (Yeloff and van Geel 2007). Cereal cultivation does not appear to cease at AQM (approximately 171 cm), c. AD 1350 (Figure 3B) but the lack of a more precise chronology prohibits any attempt to identify short-lived changes in the pollen record. Cereal cultivation possibly occurred close to the start of the plague and there appear to have been no long-term changes, possibly because the local population was not as devastated as reported elsewhere in England and there was sufficient manpower to continue farming (cf. Yeloff and van Geel 2007).

Post Medieval Period

The amount of woodland was at its lowest point since the Bronze Age by c. cal. AD 1520 (Figure 3A; 152 cm), as suggested by total arboreal pollen percentages falling to under 30%. This corresponds with an increase in the concentration of lithogenic elements and a gradual increase in Ti (Supplementary Figure 1). This represents a period of accelerated soil erosion marked by increase abundance in secondary, reworked pollen (Figure 3A). There is no evidence of an intensification of agriculture as taxa associated with arable and pastoral agricultural remain well represented but do not increase in value, except Poaceae. This might explain the continued shift in the diatoms indicating mesotrophic to eutrophic conditions highlighted by the rise of *Fragilaria construens* and the decline of *Cyclotephanos dubuis* (Figures 4 and 7).

Woodland regeneration begins from c. cal AD 1685 (130 cm; Figure 3A). This coincides with a staggered decline in the concentration of the lithogenic elements indicating a reduction in soil erosion (cf. Martínez-Cortizas et al. 2005). A downturn in agricultural activity takes place c. AD 1750 (120 cm; Figure 3B) characterised by a dip in Poaceae, a decline in cereal-type pollen and the last occurrence of a suite of coprophilous fungi which suggests that grazing was probably taking place in the catchment but not close to the mere fringe. Grassland, arable and pasture remain the dominant land use during the late eighteenth and early nineteenth century (Figure 3B). Increased pasture is indicated by the peak in Poaceae and increased *Plantago lanceolata* at 104 cm. Other pastoral indicators are also well represented in the non-arboreal pollen record. Grassland expanded from the 1960s (42 cm) as Poaceae increases to 45%: this may reflect parkland surrounding the mere

although arable cultivation continually occurs throughout the twentieth century and the presence of pasture is indicated by a suite of herbaceous taxa. There is a slow decline in cereal pollen from the start of zone AM8, but this may be due to taphonomic factors having an influence on the pollen assemblage, including the change in stratigraphy from gyttja to clay at 100 cm depth (Pittam, Foster, and Mighall 2009).

The increased representation of newly planted trees would also dilute the cereal pollen signal and the plantation of woodland immediately to the north of the mere may have acted as a barrier to cereal pollen dispersal (Maguire 1983). Trees were planted around AQM during the early nineteenth century as part of a landscaping scheme (Yale 1994) and the increases in total tree pollen coincides with higher SCP concentrations at 105 cm dating to the AD 1830s. These changes are reflected in the pollen diagram. From c. 120 cm (post-AD 1750), *Pinus*, *Picea*, *Ulmus*, *Fagus* and *Cedrus* feature more prominently in the pollen diagram. The mixture of trees planted from AD 1805–10 was documented as both semi-mature and whips (except for pine). Parkland records reveal that pine whips were planted with at least 10000 ornamental and fruit trees. Reports from the Deer Park in AD 1810 suggest that there was, ‘considerable activity ... with teams moving soil into the garden’ (Yale 1994; 36). The resultant instability within the catchment soils and subsequent erosion is detectable within the mineral magnetic signatures of the mere sediment (e.g. χ_{lf} and LOI trends in zone AM7). The S ratio declined from 115 cm to 108 cm reaching a minimum of 0.480 before recovering as part of the general increases seen in all the magnetic parameters from 102 cm upwards. Local historical maps show no, or negligible, alteration in the extent of woodland within the immediate vicinity of the mere. The only major alteration in the past century has been the planting of Castle Wood, a small area of woodland some 200 m to the south of the mere, which is not present on Ordnance Survey maps from 1892. This planting may account for the increase in total arboreal pollen percentages including *Picea* and *Ulmus* throughout zone AM8 (ca. AD 1874–2004).

Reconstructing Metal Contamination: Prehistoric Times

The source of the relatively high (albeit declining) Pb EF at the base of the AQM record, c. 1200–910 cal. BC is uncertain (Figures 5 and 7). There is no firm archaeological evidence for lead mining or metallurgy locally, although Shaw (2009) suggests that Bronze Age copper and lead mining might have taken place at Llanymynech, which is located on the Shropshire \Wales border (Figure 1F). Lead was in circulation at this time: it was being intentionally alloyed with

copper and tin to produce bronze by the Middle-Late Bronze Age during the Wilburton-Wallington Phase (1140–1020 cal. BC) (Tylecote 1986; Rohl and Needham 1998). Small pieces of lead have also been found on late Bronze Age occupation sites (e.g. Needham and Hook 1988). However, the precise sources of this lead, including that recorded at AQM, remain speculative (Barber 2003). While the elevated Pb EF at AQM also correspond to peaks in the same between c. 1100 and 800 cal. BC in a speleothem record at Charterhouse on the Mendips (McFarlane, Lundberg, and Neff 2014), it is difficult to envisage sufficient lead production during the Bronze Age to create significant pollution on a regional scale. Bronze artefacts, including axes, palstaves and trunions, etc. have been found scattered throughout Shropshire, and casting moulds for tools and weapons dating back to the EBA are also known, e.g. the Whalleybourne mould (Shaw 2009), yet these do not provide firm evidence of an early insular lead industry more local to AQM.

Late Iron Age-Roman Times

Compared to the early part of the Iron Age, Pb EF increase during the late Iron Age and Roman period (c. 265 cal. BC to AD 285) but values are not pronounced when compared to the EF values from the Bronze Age to the late Medieval period (Figure 5). Studies across Europe have shown that the most widespread pollution phase in ancient times is related to mining and metallurgy by Late Iron Age cultures such as the Phoenicians, Carthaginians, and the Greek and Roman Empires (e.g. De Vleeschouwer, Le Roux, and Shotyk 2010). The general trend commenced c. 1000–500 BC, peaked by the 1st–2nd centuries AD and collapsed by c. cal. AD 400. This is the case for Sweden, Britain, Germany, France and Switzerland (Martínez-Cortizas et al. 2013). In some regions, this chronology is so consistent that it has been suggested that it can be used as a chronological marker (Renberg, Bindler, and Brännvall 2001). This general pattern is also seen at AQM with Pb EF increasing from c. 325 cal. BC (at 359 cm) to a small peak at c. cal. 120 BC (331 cm). Three further peaks at c. 30 cal. BC, c. cal. AD 190 and c. cal. AD 270 (282 cm) are recorded. Thereafter values decline implying the cessation of any mining and metallurgical activities sometime between c. cal. AD 280 and AD 340 (274 cm) (Figures 5 and 7).

The exact source of the deposited lead at AQM is unknown. A regional anthropogenic source is more likely than a local one. There is evidence for lead working at some sites such as Wall but it is unlikely to have been on a scale to generate widespread pollution. There is no evidence that the Romans exploited copper at Ecton (Blake, Dean, and Wardle 2018). On a

wider scale, Iberia and Britain were the two major metal producing areas in Western Europe, and both Tacitus and Pliny mention the exploitation of British argentiferous lead deposits (Jones and Mattingly 1990). Even though Roman lead mining was more extensive in Iberia (e.g. López-Merino et al. 2014), potentially making this the dominant regional source for lead pollution in western Europe, the isotopic signature of lead contamination recorded in a peat profile at Lindow Bog, Cheshire, suggests a British source is more likely in this case (Le Roux et al. 2004). There are several major British lead mining areas surrounding AQM: these include north-east Wales, Shropshire to the southwest of AQM and Derbyshire to the northeast. Orefields in central Wales, the Mendips and SW Gwent are more distant to the south-west (Figure 1F). Given the predominantly SW to NE prevailing wind direction, these orefields are likely pollution sources. The closest, Shropshire, has at least 317 known abandoned lead mines (Davies and White 1981) with Roman lead pigs discovered at three of them (Shaw 2009). Dated ingots confirm that lead was mined from the Mendips by AD 49, the Flintshire mines of NE Wales by AD 74 and Nidderdale mines in Yorkshire by AD 81 (Jones and Mattingly 1990). Unequivocal archaeological evidence for mining is less forthcoming across the Shropshire and Welsh orefields (e.g. Jones et al. 2004). Roman lead smelting sites have been discovered in the Ystywth valley and Llancynfelin, near Aberystwyth (Timberlake 2002). Evidence for metal processing during the 1st century AD onwards has been identified in north-east Wales with the discovery of lead pigs (Jones et al. 2004). Roman mining did take place at Charterhouse on Mendip and at Alderley Edge in Cheshire (Todd 1996, Timberlake and Prag 2005), suggesting that local British sources contributed to the pollution recorded in bogs across Britain. Total lead production has been estimated at approximately 100,000 tons in the Mendips Orefield (McFarlane, Lundberg, and Neff 2014). McFarlane, Lundberg, and Neff (2014) consider Roman smelting to have been inefficient, citing Morgan's (1900) estimate that approximately 10% of lead used for smelting was volatilised into the atmosphere. Subsequent experiments suggest this could be far higher (e.g., Baron et al. 2009). This is corroborated by increased lead concentrations in a speleothem record from Charterhouse which shows a distinct peak in lead from 350 BC to AD 1 and increased concentrations during the Roman era (McFarlane, Lundberg, and Neff 2014). Peat records also record lead pollution during the Roman period in central Wales (Mighall et al. 2002, 2009), in north-west England (Le Roux et al. 2004) and in Scotland (e.g. Cloy et al. 2005; Küttner et al. 2014). It is surprising that an elevated Pb EF is not recorded at AQM. The pattern corresponds to Cp1

between the Bronze Age and the post-Medieval period, suggesting that the Pb EF is responding to a catchment-related process rather than providing a record of the anthropogenic Pb pollution.

Cu and Sr, which began to increase at 204 cm (c. cal. AD 985), continue to rise thereafter and remain at higher values until 130 cm (Supplementary Figure 1). The pattern of copper concentrations is similar to the lithogenic elements and therefore is probably derived from catchment soils rather than pollution from metallurgical activities. Roman copper mining occurred at Llanymynech on the Welsh/Shropshire border but there is no evidence for any medieval workings (Jones and Mattingly 1990). Copper concentrations during the Roman period are not elevated relative the rest of the profile at AQM and they remain much lower than those recorded during the medieval period.

Anglo Saxon

Between c. cal. AD 340 and c. cal. AD 525 (274–254 cm) Pb EF values are much lower (Figures 5 and 7). They recover to slightly higher values, albeit much lower than those recorded during Roman times, possibly suggesting a small revival in lead mining and/or metallurgy by c. cal. AD 660 (240 cm) until they decrease gradually to c. cal. AD 1025 (204 cm) which might equate with the beginnings of a proto-English state under King Athelstan and the subsequent disruption caused by the Viking invasions and the Norman Conquest. Although archaeological evidence for lead mining has not been forthcoming, evidence for lead metallurgy to make objects, assisting the working of other base metals, for cupellation and glass making, is relatively common across late Saxon and Viking England (Bayley 1992). Lead contamination, possibly caused by small scale mining/ metallurgical activity, was also recorded in an ombrotrophic bog near Leadhills/ Wanlockhead during the 5th–7th and 9th–11th centuries AD (Mighall et al. 2014) and elsewhere in southern Scotland (Küttner et al. 2014). The post Roman period is typically characterised by much lower lead contamination in bogs across Britain (e.g. Le Roux et al. 2004), in the speleothem record at Charterhouse and the archaeological record also provides little evidence of substantial lead working (Shaw 2009; McFarlane, Lundberg, and Neff 2014).

From 204 cm (c. cal. AD 1025) there is a very gradual increase in Pb EF. A slight interlude of lower concentrations between c. cal. AD 1150 and cal. AD 1340 (192–172 cm) suggests that the level of mining activity was temporarily affected, possibly by the Black Death and the onset of the hundred years war (Le Roux et al 2004; Shaw 2009; McFarlane, Lundberg, and Neff 2014), although there are historical references to lead use in Shropshire from the cal. AD 1220s to the

1270s (Shaw 2009) and mining of silver-rich lead ores in Devon (Claughton 2009). By c. cal. AD 1340 (172 cm; Figures 5; 7) there is rapid and sustained rise in values which continued until c. cal. AD 1520 (152 cm). Local, British ores appear to have been exploited during this time and this is also reflected by the sustained rise of lead recorded at Lindow bog (Le Roux et al. 2004). References to mining in Shropshire become more abundant during the early medieval period but later medieval references are scarce in Shropshire, although Shaw (2009) suggests that it is unlikely lead mining ever ceased and this view is also supported by the increase in Pb EF at AQM. Assuming the Pb EF record is a faithful record of changes in level of lead and silver mining and associated industries (cf. Mighall et al. 2006), mining and metallurgy in the later medieval period appears to have been sustained to supply lead for monastic and military purposes (Bailly-Maitre 2002). By the close of the medieval period, demand for metals, including lead, was met by mines being worked on non-argentiferous lead deposits in the Mendips, NE Wales, Derbyshire, Yorkshire and the northern Pennines (Claughton 2009). Another sharp increase in Pb EF occurs around c. cal. AD 1600 (142 cm), consistent with the continued development of lead mining across the British Isles. Lead mines were subject to technological developments such as new furnaces and demand for lead across Europe between AD 1500 and 1670 (Claughton 2009; Shaw 2009) and this is clearly reflected at AQM and in bogs elsewhere in the British Isles (e.g., Le Roux et al. 2004). Pb EF continue to increase at AQM coinciding with the early stages of the Industrial Revolution as the demand for lead steadily increased throughout the AD 1600 and 1700s (Burt 1969).

Modern Period

A high Pb EF is recorded at Aqualate Mere from the late seventeenth century through to the 1960s (Figure 5). Notwithstanding slight variations in timing, this is a common feature of lead concentration and accumulation rates in the British Isles and Europe, caused by increased lead smelting, coal combustion and use of leaded gasoline (e.g. Livett et al. 1979; Mighall et al. 2002, 2009, 2014; Küttner et al. 2014; De Vleeschouwer et al. 2010). In common with previous studies near-surface and surface Pb EF is much lower at AQM. This decline is most often attributed to the phasing out of leaded gasoline.

The changes observed in the top metre are the result of a change in sediment source (Pittam, Foster, and Mighall 2009). All the lithogenic elements and some trace metals (Cu, Sr) decrease in concentration as Ca, P and Zn increase (Figure 5). Industrial development in the West Midlands (e.g. Crompton 1991;

Stobart and Raven 2005) is a likely source for the rise of Zn and Pb in the top 40 cm. Sources include a coal-fired power station at Coalbrookdale, ca. 10 km to the south-east, and the development of a metallurgical industry at Wolverhampton (ca. 15 km to the south-west) (Pittam, Foster, and Mighall 2009), where soil zinc concentrations up to 2045 $\mu\text{g g}^{-1}$ have been recorded (Kelly et al. 1996). The results are also consistent with elevated concentrations of heavy metals in post-AD 1900 urban and rural lake sediments elsewhere in the English Midlands (Foster et al. 1991).

Conclusions

The multiproxy approach applied to the Aqualate Mere (AQM) sediment sequence has provided palaeoecological evidence of human activities from later prehistoric times – woodland clearance, farming intensification, soil erosion, and regional lead pollution – for an area, the English Midlands, for which scant information was previously available. The record reflects short-lived clearances (c. 1115–1085 and 965–905 cal. BC), and agriculture (cereal continuously recorded, including rye and arable and pastoral non-arboreal taxa and coprophilous fungal spores). Although ‘social discontinuity’ has been proposed as cause of woodland regeneration in some areas of southern England, our record suggests continuing agriculture in the Midlands. As a result, the chemistry of the lake may have been impacted leading to a shift in the diatom flora to species with more eutrophic preferences. Further agricultural expansion seems to have taken place during the later Iron Age.

For Roman times, we have found evidence of clearances, cultivation (mainly cereals) and pastoral activities around AQM, despite being assumed that the local population was small and possibly was not wholly affected by Romanisation. Increases in rye pollen were coeval with clearances of the oak woodland, indicating increased food production possibly to supply and service the Roman Army and sustain a growing population. Abandonment of cultivation, woodland regeneration and a shift to pastoral-based agriculture seems to have occurred more widely by the end of the Romano-British period, but evidence for this is not as clear in AQM, as our data suggests a mixed agrarian economy continued into the Anglo-Saxon period with no major disruption.

Substantial woodland areas remained in the AQM catchment until the post-medieval period. The lowest forest cover occurred by the early sixteenth century when total arboreal pollen fell below 30% TLP and coincided with evidence of accelerated soil erosion. Woodlands may have regenerated by the end of the seventeenth century, but grassland, arable land and pasture remained the dominant land use until the early nineteenth century.

Regarding atmospheric metal pollution, the AQM sequence resembles the general pattern found in other studies in Europe with the earlier phases of pollution occurring between 325 and 120 cal. BC but it is unlikely to be reflecting local activities but a more regional pollution signal. Regionally, lead pollution seems to have peaked by the early 1st century AD and declined by the later 3rd to the mid-4th century AD, suggesting a near-cessation of mining and metallurgical activities. Pollution resumed after the mid-7th century AD, only to decline once more between the 11th and 13th centuries AD. Atmospheric metal pollution rose again from the early fourteenth century AD, with two periods of acceleration at the end of the seventeenth century and by the early twentieth century AD. Two reviewers kindly provided constructive suggestions that improved the manuscript.

Acknowledgements

We wish to thank Coventry University for funding a PhD project (Pittam), Bob Hollyoak and Liz Turner for laboratory assistance, Alison Sandison and Jenny Johnson at the University of Aberdeen for drawing the diagrams and Neil Rose kindly provided advice with regard to the SCP analysis.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by Coventry University.

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