

The magnetic record of inorganic fly ash deposition in lake sediments and ombrotrophic peats.

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Abstract

Interest in identifying a geological marker signifying the starting point for the Anthropocene has prompted an exploration of the stratigraphic record of inorganic particulates generated by industrial activities. Magnetic measurements of recent lake sediments and ombrotrophic peats are here used to reconstruct the history of deposition of inorganic fly ash spheres resulting mainly from solid fuel combustion and metal smelting. The chronologies used have been based on moss-increment counting, radioisotope dating and pollen analysis. The sites come from the United Kingdom, Scandinavia and North America. In several cases where detailed chronologies of both fly ash deposition and local industry can be compared, the sequence of concentration-linked magnetic measurements appears to capture accurately the record of industrial development despite incontrovertible evidence from other peat based records for some selective dissolution of magnetic minerals. The dates at which magnetic concentration increases begin range from the 16th century in the peat profiles around the head of Morecambe Bay, South Cumbria, in North-West England where early iron manufacture using charcoal-fuelled bloomery hearths is well documented, to the mid 20th century at the remotest sites in Arctic Scandinavia. The lake sediment profiles used here come mainly from the United Kingdom and, in most cases, they date increases to the late 19th century or the first decades of the 20th century. Any attempt to use the magnetic record of fly ash deposition in lake sediments and/or peats to mark the date chosen as the onset of the Anthropocene would require careful choice of site location and archive, bearing in mind the issue of selective magnetic mineral dissolution.

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Introduction

The proposal that the Anthropocene should be recognised as a new geological epoch raises the question of what might constitute a suitable marker for its inception. In the original definition of Crutzen and Stoermer (2000), the onset is placed during the early stages of the Industrial Revolution which were, prior to the emergence of oil as a dominant fossil fuel-based energy source and the development of the internal combustion engine, literally fuelled by coal. Coal combustion and many associated heavy industries such as iron and steel manufacture and metal smelting, generate residual, un-combusted mineral particles many of which leave the site of combustion as particulate pollutants in the atmosphere. These particulates are often referred to under the generic term 'fly-ash'. Rose (1994) divides fly-ash into organic and inorganic fractions, the former comprising spherical carbonaceous particles (SCPs) and the latter inorganic ash spheres (IAS). It is with these latter (Fig. 1) that the present article is concerned. Rose (1990) details a chemical extraction technique for isolating IAS but here, we focus on non-destructive, magnetic methods of detection and measurement.

Previous publications (Thompson and Oldfield, 1986 ; Oldfield et al. 1978; Thompson et al. 1980; Oldfield et al. 1981; Anderson et al. 1986; Richardson, 1986; Tolonen and Oldfield, 1986; Battarbee et al. 1988; Fritz et al. 1989; Patrick et al. 1989; Oldfield and Richardson 1990; Renberg et al. 1990; Oldfield, 1991; Snowball et al. 2013) confirm that magnetic records from both lake sediments and peats can shed light on the history of atmospheric deposition from industrial activities. Moreover, these records also show that (i) the spatial distribution of the inventories of atmospheric deposition captured by magnetic measurements (Thompson and Oldfield, 1986) reflects the spatial distribution of heavy industry, solid fuel-based power generation and coal combustion in Europe, (ii) where direct comparisons can be made between dated records of magnetic deposition and local industry there can be a compelling match between the two (Oldfield et al. 1981; Tolonen and Oldfield 1986) and (iii) dates for the onset of the magnetic record of atmospheric deposition sometimes lie close to Crutzen and Stoermer's preferred date (AD 1800) for the start of the Anthropocene. At the same time, Williams (1992) has shown and subsequent work has confirmed that despite the apparent credibility of some magnetic records of atmospheric deposition in peat, there is incontrovertible evidence for partial dissolution of the record at some sites.

Particles of IAS arising from coal combustion are rich in both haematite and magnetite (Tishmack and Burns 2004; Winburn et al. 2000; Sharonova et al. 2003; Bhattacharjee et al. 2013), as well as heavy metals such as lead and zinc. The former two can be recognised and their presence partially quantified by means of magnetic measurements (Oldfield, 1991; Oldfield 2012; Liu et al. 2012). Particulates rich in these components have been widely dispersed in the atmosphere from the beginning of the Industrial Revolution. They are

readily incorporated in accumulating lake sediments and peats, both of which are widespread in many industrialised areas and both of which often accumulate sufficiently rapidly to provide a detailed stratigraphic record. Whereas lake sediments usually also contain magnetic minerals derived from the lake catchment and/or from biological productivity within the lake, the so-called ombrotrophic (rain-fed) peat bogs (Clymo, 1984) which are, by definition, raised above the ground water-table, are nourished entirely by atmospheric deposition. They therefore occupy a prime position in archives of particulate pollution history, though one that is not without problems and challenges, as noted below.

The text that follows presents a summary of lake sediment and peat analyses carried out mainly during the 1980's and 1990's. The examples chosen are representative of 36 lake sediment records and over 200 peat cores, together comprising a total of over 70 sites, mainly in the UK, Europe and, to a lesser extent, in North America. Many are from unpublished PhD dissertations (Jones, 1985; Jones, 1986; Gedye, 1998) by graduate students from the then Department of Geography, University of Liverpool. Wherever possible, the records used in the present account include chronological information giving, at the very least, some indication of the depth at which the record of industrial deposition begins. The dating methods used are based on a range of techniques:

Annual moss increment counting (Pakarinen and Tolonen, 1977). This relies on the strong seasonality that controls the growth of moss (notably *Sphagnum* and *Polytrichum*) species in continental climates. It can give accurate and precise chronologies down to the depth at which the annual growth increments are no longer recognisable owing to decomposition. Below this depth, an accumulation model detailed in Pakarinen and Tolonen (1977) extends the chronology back in time, but with less precision and accuracy.

- A. *Short-lived radioisotope dating.* The main radioisotope used is lead 210 (^{210}Pb) which, under ideal circumstances, can be used to date the last 100 – 150 years. Its application to lake sediments is outlined in Appleby (2001; 2008) and to peats in Appleby, Shotyk and Frankhauser (1997) and Oldfield, Richardson and Appleby (1995). A single dated profile on its own and without independent constraints is often problematical and ^{210}Pb is best used in conjunction with the isotopes caesium 137 (^{137}Cs) and americium 241 (^{241}Am). Both have been around since post-1945 nuclear weapons testing in the 1950s and both had peak deposition in 1963 in the northern hemisphere and a year later in the southern hemisphere. Caesium, but not americium, was also widely distributed in the northern hemisphere as a result of the Chernobyl accident in 1986 (van der Post et al. 1997). Both often provide reliable constraints on ^{210}Pb dates in lake sediments, but ^{137}Cs especially can become mobile in acid peat, which greatly reduces its value as a chronological marker. Even more valuable as constraints on ^{210}Pb based chronologies are independent markers as detailed below and illustrated in Figure 2.
- B. *Pollen analysis.* Some of the changes in agricultural practices that can be securely dated from documentary evidence can also be recognised in pollen diagrams

spanning the last few centuries. They can therefore be used as important constraints on radioisotope dates. In NW England especially, one of the most useful in the present context is the demise of hemp (*Cannabis sativa*) cultivation during the second half of the 18th century as a consequence of the increasing importance of jute from abroad (Housman, 1800; Oldfield and Statham 1963; Richardson 1986). In N America, the spread of weeds in the wake of European settlement has also left an important marker in the pollen record – the appearance and increasing representation of the weed *Ambrosia artemisiifolia* (Richardson 1986).

- C. *Radiocarbon dating*. Individual radiocarbon measurements are of little use in dating sediments and peats spanning the last 2 – 3 centuries. Chronologies can however be established by mapping a sequence of closely spaced ‘dates’ onto the calibration curve derived from comparing radiocarbon activity variations with tree rings (Fig. 2).

Magnetic measurements

The advantages of the magnetic approach include: non-destructive measurement with minimal pre-treatment, detection of magnetic minerals at concentrations orders of magnitude below those achieved by conventional techniques and some partially quantitative discrimination between different magnetic mineral contributions. The disadvantages include the fact that the relationship between the measurements and magnetic mineral concentrations is not precisely quantifiable. During the period when the reported results were obtained, the equipment available for magnetic measurements changed and the methodology evolved in response both to these changes and to increasing experience of what, at the time, was still a new approach to environmental research. The following magnetic properties are used and interpreted as follows:

Saturation Isothermal Remanent Magnetization (SIRM) measured in a DC field of 1T or, in the case of some early analyses, 850mT. This is used here to provide the best available indication of changes in total magnetic mineral concentrations. In the present measurements, SIRM values mainly reflect changes in the concentration of magnetite since it is some two orders of magnitude more magnetic than the other main component, haematite. In Figures 5, 6, 7, 8 and 10, SIRM values are shown as proxies for concentration. In Figures 3 and 9, the values have been recalculated as an accumulation rate per unit area.

Hard Magnetic Remanence (HIRM) expresses that part of the original SIRM that remains unreversed in a high reverse field (here usually -100mT or 300mT). In Figure 4a it is used as a proxy for changing haematite concentrations, in Figures 3, the HIRM values have been recalculated as an accumulation rate. In Figures 5, 6, 7, 8 and 10 they are shown alongside the SIRM profiles and expressed as percentages of SIRM unreversed, indicating the changing contribution of haematite *relative* to the total magnetic mineral record.

Methods of measurement and calculation as well as the basis for interpreting these measurements are detailed in Oldfield (1999).

Depositional histories

Lake sediment records

Examples referred to are from sites in Great Britain (Oldfield and Richardson, 1990; Battarbee et al. 1988), Sweden (Renberg et al. 1990) and the United States (Oldfield, 1990). Each of the cores analysed, with the exception of that from Grey Heugh Slack (Battarbee et al. this volume) was taken in the 1980s either as part of the SWAP (Surface Water Acidification Project) in Europe (Battarbee et al. 1990), a UK Department of Environment Programme or the PIRLA project (Paleocological Investigations of Recent Lake Acidification) in North America. All were carried out with a view to establishing the history of industrial atmospheric deposition in relation to the onset and progress of lake acidification. In all cases where dates are given, they are based on ^{210}Pb analyses.

British sites. A total of 39 suites of magnetic measurements from 32 sites were completed as part of the SWAP and related programmes (Battarbee et al. 1988). Three well-dated cores, from Scotland (Lochnagar; Loch nah Achlaise) and Wales (Llyn Dilyn) are used in Figure 3 as examples.

At Lochnagar, as in all the dated profiles from the most remote Scottish sites, there is no evidence for any significant increase before AD 1900. Slight increases occur between 1900 and 1950, with the most dramatic increases after 1950. Llyn Dilyn in Snowdonia, NW Wales, Loch nah Achlaise 60 km north of the industrialised Clyde Estuary and also Scoat Tarn in the English Lake District, (Battarbee et al. 1990) are less remote from areas of heavy 19th century industrialization in S Wales, Scotland and N England respectively. In these cases, there are clear indications of increasing magnetic concentrations prior to 1900, steady increases around 1910 - 1925 and, in the case of Llyn Dilyn, a further sharp increase in the mid-20th century. At Grey Heugh Slack on the North York Moors in NE England, magnetic deposition begins to increase in the early 19th century alongside other geochemical markers of industrial activity (Battarbee et al. this volume).

Lilla Oresjon, SW Sweden was one of the key sites in the SWAP programme. As Figure 4a shows, there is some indication of a low, sustained increase in haematite concentrations from AD 1900 onwards followed by a sharp increase after 1960. There are similar indications from the record of SCPs, PAH (poly-aromatic hydrocarbons) and lead concentrations in the same core (Renberg et al. 1990).

Big Moose Lake, New York State, USA lies in the Adirondack Mountains. It was part of the N American PIRLA project (Charles and Whitehead, 1986). The detailed ^{210}Pb chronology allows the results to be expressed as an accumulation rate. Comparison

between two analysed cores led Oldfield (1990) to conclude that the 'hard' remanence broadly representative of haematite deposition was the least ambiguous indicator of atmospheric deposition at the site. Figure 4b shows the changing accumulation rates of this component in two cores from the site. There is no sign of any significant increase prior to AD 1890, after which a steady increase is recorded in both cores, peaking at the end of the record in the late 1970's.

Ombrotrophic peatland records

North West England – Morecambe Bay peatlands, South Cumbria. Even before the beginning of the 18th century small scale iron production took place in the area, using local iron ore and charcoal fuelled 'bloomeries'. During the second decade of the 18th century, the local iron industry began to expand rapidly with coke-powered blast furnaces common by AD 1750 (Awty, 1979-80). Heavy industry based on nearby iron and coal continued until the early decades of the 20th century.

Richardson (1986) demonstrated that a strong increase in magnetic mineral concentrations at Heathwaite Moss, one of several ombrotrophic bogs in South Cumbria, round the head of Morecambe Bay began shortly after the end of hemp (*Cannabis*) cultivation around AD 1800. Using a more comprehensive approach to chronology involving ²¹⁰Pb, ¹³⁷Cs, ²⁴¹Am, wiggle-matched ¹⁴C and a range of pollen markers, Gedye (1998) produced 12 dated profiles of magnetic measurements from three peat bogs in the region. In all but one of these the first stage of SIRM increase occurs before AD 1800 and, in 5 cases, before AD 1550 (Figure 5).

Figure 6 shows the results from two cores taken more recently from the region. The cores were selected to represent a contrast in moisture status, with the peat at the marginal site dried out. The SIRM values are over an order of magnitude higher in the latter. There is also a contrast in the reverse field percentage values with the marginal site showing no change in unreversed hard IRM% and the wettest site showing a strong peak. This increase in the *relative* importance of the likely haematite contribution to the SIRM is a common feature of many of the magnetic profiles from peat (Figs. 7, 8 and 10) and its significance is considered in the Discussion.

Galloway, SW Scotland. Of the 12 cores from Ellergower Moss included in the SWAP programme and summarised in Clymo et al. (1990), the results from well-dated core EM 4 (see Fig. 2) are used to illustrate the record (Fig. 7). Although the main increase in SIRM lies at 20cm, above the AD1835 level, there are indications of slight increase at 27cm, just above the increase in the percentage representation of HIRM at 28cm. The ²¹⁰Pb profile indicates a date close to AD 1800.

Bloak Moss, eastern lowland Scotland, Three cores from this site (Richardson 1986) allow direct comparison between the magnetic record and dated pollen horizons. In each case, magnetic concentrations begin to increase just before early increases in *Pinus* and *Ulmus* pollen representation reflecting late 18th and early 19th century plantation.

Ringinglow Bog, N England lies on the southern edge of Sheffield which, along with industrial centres in N Derbyshire, was a major centre of iron and steel based industry during the Industrial Revolution. Coke fired iron smelting in the region dates back to the mid-18th century and the industry increased to the point where, by 1856, there were 135 steel-making firms in Sheffield. Figure 8 illustrates the record from Ringinglow Bog. The first increase in SIRM is preceded by an increase in the percentage contribution of hard remanence (haematite) to the total SIRM, typical of all 5 of the cores analysed (Jones 1985). Using a combination of ²¹⁰Pb, pollen and ¹⁴C analyses, Jones dates the base of the HIRM feature to 1830 – 1850 and the main increase in SIRM to 1900 - 1920.

Peat profiles from Finland. Of the 4 sites studied by Oldfield, Tolonen and Thompson (1981) the most detailed record comes from Karpansuo bog. Four moss-increment dated profiles present a generally consistent picture with indications of very slight increases in deposition around AD 1860, followed by steady increases after 1900. The record from Kunonniemensuo, a site further east in Finnish Karelia provides a less detailed but parallel record. Shorter profiles from other sites show varied records depending on proximity to industrial sources. The Harpar Lilltrask site lies only 7.8 km north-west of the steel works at Koverhar which began iron production in 1961 and steel production in 1971. The magnetic record appears to reflect this industrial development very clearly.

Additional profiles from Finland, all dated by moss-increment counting are reported in Jones (1986). At Kaurastensuo Bog in C Finland, in the 4 cores with good chronology and in which both an initial increase and a subsequent more rapid increase to peak values can be recognised, dates for the earlier feature range from 1840 to 1900 and, for the later feature, from 1900 to 1940. Jones (1986) also records the results of analyses of 6 dated peat profiles from sites close to and north of the Arctic Circle. In those cores for which a clear change in magnetic accumulation rates can be detected, the dates range from 1920 to 1960. In 6 of the 8 cores analysed, there is a marked increase from ca.1950 onwards. In Norway, Jones (1986) also analysed a dated profile from 36km south of Mo-I-Rana, the site of a major iron ore complex. Here, the SIRM values begin to increase around 1860 and rise steeply from 1940 onwards. In Denmark, Jones (1986) also obtained data from a ²¹⁰Pb dated core from Draved Moss. Here, there are slight increases in SIRM between ca 1810 and 1890, but the first clear rise in values is around 1920 with a much steeper increase from 1950 onwards.

Regent Street Bog, Fredricton, New Brunswick, Canada yielded two cores which were analysed both for magnetic mineral deposition and a range of heavy metals (Tolonen and Oldfield, 1986). Figure 9 shows some of the data expressed as accumulation rates per year, alongside the dates of the main stages in industrial development in the area. The record shows magnetic concentrations increasing just before AD 1800, after the establishment of lumber mills. The second, larger increase is around the time of

establishment of a foundry and brickworks. Closing of the foundry around 1930 led to a steep decline in magnetic deposition.

An additional N American site, *Ely Lake Bog* within the Mesabi Iron Range, Minnesota, was studied by Richardson (1986). The characteristic increase in HIRM% coincides with the increase of *Ambrosia* pollen representation, dated to the same time as the start of iron mining in AD 1888. SIRM values increase from this time onwards (Fig. 10). Figure 1 includes SEM images of ash spheres from the surface and from the depth of maximum HIRM% values. The latter images show clear signs of dissolution.

Adjacent lake sediment and peat records

The record from Llyn Hir, a small lake in the uplands of Central Wales may be compared directly with that from nearby peat profiles taken from the lake catchment (Fritz et al., 1986; 1989). Both the lake sediment profiles and the record from the adjacent peat bog show an early stage in inferred atmospheric deposition marked by higher unreversed IRM% values. In the case of the peat record, the SIRM values are much higher in the more aerated 'hummock' core, relative to the more persistently water-logged 'pool' core.

Discussion

Background values

Since, by definition, ombrotrophic peats lack any input of magnetic minerals other than those resulting from atmospheric deposition, the question of background values does not arise, though, in some peat profiles, there are tiny traces of a ferrimagnetic sulphide mineral, greigite, formed *in situ* by the transformation of non-magnetic iron compounds (Oldfield, 2012). The concentrations are so low that they do not significantly affect the record of atmospheric deposition.

In the case of lake sediment records, where the signs of atmospheric deposition have to be distinguished from magnetic minerals arising from other sources, problems arise both from the presence of eroded material from the surrounding land surfaces and from magnetic minerals formed in the sediments themselves. These latter include magnetite 'chains' formed by bacteria, as well as greigite. Only where these various types of magnetic mineral sources are negligible or, at the very least low and constant, is a clear record of atmospheric deposition decipherable.

Problems of depths and accumulation rates

The ideal record is one where the sequence of dates in an analysed profile is sufficiently detailed to permit the calculation of mineral *deposition rates* between reliable dates (Figs. 3, 4b and 9). The next best alternative is where the magnetic measurements, as indicators simply of changing *concentrations*, can be plotted against a timescale or isolated dates (Figs. 4a, 5, 6, 7, 8 and 10). In this case, two major variables control the

shape of the plot – the rate of deposition/preservation of the magnetic minerals and the rate of accumulation of the sediment or peat. In the case of peat especially, this can lead to changes strongly controlled by a steep decomposition gradient across the transition from undecomposed peat in the upper, acrotelm and much more decomposed peat in the catotelm, below within which the rate of accumulation is often around 10% of that for the fresh peat nearer the surface. This has the effect of diluting concentrations near the surface relative to those at greater depths. Thus, although peat profiles may record the start of deposition, the changes above this may not represent stages in deposition history unless they can be converted into *deposition rates*.

Links to local industrial history

Figure 9 shows the only example used here where the deposition history has been reconstructed and dated in sufficient detail at a site close to a location for which the industrial history is well known. In this and in examples from Finland (Oldfield et al. 1981), the records come from ombrotrophic bogs dated by annual moss increment counting in the upper layers. In each case, they appear to reflect the local, industrial history in a remarkably accurate manner. Most of the other records are dated with less precision and accuracy, lack close links to nearby industry, or are the result of industrial changes for which detailed records are not available. For many of these, the key question concerns the evidence for survival or progressive degradation of the magnetic record.

Questions of survival

The first essential assumption needed in interpreting the results is that the magnetic measurements, used as surrogates for concentrations of the actual minerals, are reliable for the present purposes of establishing the beginning and main trends in magnetic mineral, hence inorganic ash sphere (IAS) deposition. Williams (1992) has shown that dissolution of magnetic minerals occurs alongside the decomposition of organic matter as fresh bog vegetation is converted to peat, especially across the acrotelm/catotelm transition noted above.

One of the most frequent characteristics of the peat records is an increase in unreversed IRM% roughly coinciding with the earliest stages of SIRM increase. This feature is illustrated in Figures 6, 7, 8 and 10. It reflects an increase in the importance of haematite relative to magnetite during the earliest stages of industrial deposition. As Figure 6 shows, there is a gradient linking the strength of the feature to the wettest site. The profile from Helsington Moss shown in Figure 5 comes from a dried out, residual rampart of peat surrounded by lower, drained, agricultural land from which peat has been removed for fuel. As in the driest site shown in Figure 6, there is no inflexion in the unreversed IRM% curve. The SEM images shown in Figure 1 show strong evidence for dissolution of the fly ash spherules at the base of the 'kink' in unreversed IRM% values at Ely lake Bog (Fig. 10). Taken together, all these lines of evidence point to a likely link between the dissolution process identified by Williams (1992) and the greater relative

importance of haematite in the earliest stages of fly ash deposition. Rothwell and Lindsay's (2007) evidence from Pennine peats, also points to a close link between survival of the magnetic record and the degree to which peat has dried out along the edge of drainage gulleys. Hubbard et al. (1984) note that whereas magnetite forms during the coal combustion process and is characteristic of the outer rim of the spheres produced, haematite is more likely to be a residual survivor from the original mineral content of the coal. This may contribute to selective survival. Despite the effects of selective dissolution, the magnetic mineral record of atmospheric deposition in peat, though incompletely preserved in many cases, may, for several centuries in the case of the peat records from South Cumbria, retain a clear indication of the earliest stages in the deposition of industrially generated inorganic ash spheres. Longer term survival of the magnetic evidence cannot be confirmed. The parallels between the adjacent lake sediment and peat profiles at LLyn Hir (Fritz et al. 1989) suggest that selective dissolution may also affect acid, organic lake sediment sequences.

Dating the beginning of 'fly-ash' accumulation

From the wealth of data summarized above and in Table 1, it is clear that no single synchronous horizon common to all sites can be defined using magnetic records of fly ash deposition. Where sufficiently detailed comparisons can be made between the chronology of magnetic deposition and local industrial history the correspondence is quite close and convincing, but industrial histories vary between sites and regions. The earliest clearly documented and reliably dated increases in deposition of inorganic fly ash come from NW England and just predate the mid 16th century. This roughly corresponds with the time that Fischer-Kowalski, Krausmann and Pallua (2014 in press) favour as the socio-metabolic onset of the Anthropocene. Limited chronological data from e.g. Ringinglow Bog in the industrial heartland of northern England suggest that at such sites, the onset of magnetic accumulation corresponds quite closely to the early industrial date favoured by Crutzen and Stoermer (2000), but questions regarding the long-term survival and detection of the onset of magnetic deposition in peat remain to be resolved. In sites more remote from early industrial regions, the record of detectable deposition begins any time between the beginning and middle of the 20th century and many sites show a major increase in magnetic deposition roughly coinciding with the mid-20th century 'Great Acceleration' in energy use documented by Steffen, Crutzen and McNeill (2007). The pattern revealed here is therefore more complex than that proposed by Snowball et al. (2013). The results as whole confirm the value of magnetic measurements as providing a temporal and spatial record of a dominant energy source and stage in industrialization. Their record is complementary to that obtainable from a range of other industrial markers, for example, heavy metals, SCPs, PAHs and pesticide derivatives.

The signatures derived from peats and lake sediments are essentially regional, save perhaps in the case of the results from the most northerly Scandinavian sites (Table 1). Early attempts to compile a magnetic record from ice cores (Sahota et al. 1996) failed to

detect any signal above the noise level of the instrumentation then available, save in the case of Himalayan samples. More recent research in both Greenland and Antarctica (Lanci et al. 2001; 2007; 2012; Lanci and Delmotte 2013) confirm that current instrumentation can detect and characterize effectively the magnetic properties of ice both in Greenland and Antarctica, but the thrust of the work so far has been towards documenting dust sources characteristic of glacial and interglacial periods. These results together with those summarised in the present account and the records of heavy metal deposition retained in Greenland ice (Candelone et al. 1995) suggest that Greenland ice cores spanning the industrial period will contain, at the very least, a northern hemispheric magnetic record of 20th century fly-ash deposition.

Conclusions

Depending on the site and its proximity to sources of heavy industrial activity, the date of onset of fly-ash deposition can vary from the 16th to the mid 20th century. Thus, seeking a so-called 'golden spike' with which to define the onset of the Anthropocene by using the deposition record of inorganic ash spheres (fly-ash) in peat and lake sediments poses a complex mixture of problems and opportunities. Selection of an appropriate site to provide a record capable of defining the onset of the Anthropocene first requires a choice between the early stages of the Industrial Revolution around AD 1800 and the start of the Great Acceleration around AD 1950. The record preserved in lake sediments and peats appears to be capable of defining either, depending on the site and type of environmental archive chosen. That said, questions remain in the case of peat-based records as to the long term survival of the magnetic minerals used here as proxies for fly-ash deposition. This calls for further geochemical research coupled with magnetic measurements, scanning electron and more detailed chronologies of deposition history in relation to the documented history of industrial activity in the region selected. Future priorities could also include extension of this approach more widely, in Asia for example, as well as analysis of recent ice cores.

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Figure Captions

1. Pictures of inorganic fly-ash spheres from Ely Lake Bog (Fig. 10). I(a) and 1(b) show fly ash spheres from the 2-3cm depth. Figures 1(c) and 1(d) are from 14-16cm depth and show signs of surface degradation.
2. Chronology of recent peat accumulation based on wiggle matched ^{14}C , ^{210}Pb , ^{241}Am , pollen correlations and historical evidence: Ellergower Moss, Galloway, SW Scotland (Oldfield et al. 1995). (a) shows successive, contiguous ^{14}C 'dates'

for Core EM3, mapped onto the tree-ring based calibration curve. Pollen data from the same core show the increase in *Pinus* pollen frequency between inflexions B and C, with an interpolated date of ca AD 1835. (b) shows the wiggle-matched ^{14}C dated inflexions and the *Pinus* pollen increase in Core EM3 plotted against depth and Year AD. (c) shows the results of ^{214}Am determinations for Core EM4. (d) plots the ^{210}Pb derived age-depth curve for Core EM4 with, superimposed on it, the *Pinus* increase date based on pollen correlation between EM3 and EM4, the ^{241}Am dates and the age of the final increase in *Pinus* pollen frequency reflecting recent, commercial afforestation. Ages are from AD 1990.

3. SIRM accumulation rates in three lake sediment cores from Scotland and Wales. (a) Lochnagar in the Cairngorms, NE Scotland; (b) Loch nah Achlaise, SW Highlands, Scotland; (c) Llyn Dulyn, Snowdonia, N Wales.
4. Lake sediment records from S Sweden and the Adirondacks, New York State, USA. (a) shows selected data from Lille Oresjon (Renberg et al 1990). (b) shows the record of 'Hard' IRM accumulation in two cores from Bigmoose Lake (Oldfield, 1990). In both plots, the 'hard' IRM (remanence remaining at -300mT) has been isolated to avoid the effects of magnetite derived from the catchment. Whereas plot (a) shows 'hard' IRM as a proxy for changing concentrations, the detailed chronology allows the values in plot (b) to be recalculated as a changing accumulation rate.
5. Helsington Moss, South Cumbria; a dried out 'rampart' of peat. Core HM1. (a) maps the ^{14}C 'dates' onto the dendrocalibration curve and also notes the depth at which the steep decline in *Cannabis* pollen indicates a date close to AD1800. (b) shows the changing SIRM values against depth, with dates added. The decline in SIRM values above 15cm reflects dilution by increasingly undecomposed peat rather than changes in atmospheric deposition. The unreversed IRM% values at -100mT and -300mT, show no change through the period of increasing SIRM values.
6. Fishhouse Moss, South Cumbria, UK: profiles of SIRM and unreversed IRM% values (at -100mT). Note the contrast in peak SIRM values and in the unreversed IRM% curves.
7. Ellergower Moss, Galloway, SW Scotland. Core EM4. SIRM values are shown against depth, also the unreversed IRM% values at -100mT. The dates added are transferred from the chronology shown in Figure 2. Note the major increase in unreversed IRM% above 25cm.
8. Ringinglow Bog, S Yorkshire, N England (Jones, 1985). HIRM plotted against depth. The slight increase at 36cm coincides with a major increase in unreversed IRM%.
9. Regent Street Bog, Fredricton, New Brunswick, Canada. SIRM values plotted as accumulation rates against a timescale derived from moss increment counting. Dated events in the industrial history of the local area are added (Tolonen and Oldfield 1985).

10. Ely lake Bog, Minnesota, USA. Pollen and IRM data from two cores. In both, the increase in IRM_{850m} coincides with the first increase in Ambrosia pollen representation, dated to AD 1890 (Richardson, 1986). It is also marked by a strong relative increase in hard remanence unreversed IRM%. The SEM images in Figure 1 come from the upper, hummock profile.

	First detectable increase	Subsequent steeper increase ¹
LAKE SEDIMENTS		
Scottish Highlands	Between 1900 & 1950	~1950
English Lake District	Pre 1900	~1910
Upland Wales	Pre 1900	~1910
SW Sweden	~1900	1960
Adirondack Mts., NE USA	Steady increase from ~ 1890 onwards	
OMBROTROPHIC PEAT		
Morecambe Bay, NW England ²	Initial increases mostly pre 1800 and often pre 1550	
Galloway, SW Scotland ²	~1800 with some acceleration around 1835	
Eastern lowlands Scotland ²	~1800 or slightly earlier	
Ringinglow Bog, N England ²	~1835 with steep increase around 1900 -1920	
S Finland	~1860	~ 1860
SE Finland (near Koverhar steel)		1961 - 1971
Central Finland	1840 - 1900	post 1900
N Finland	post 1920 with steep increases ~ 1950 in most cases	
N Norway (near Mo-I-Rana iron)	1860	1940
Fredricton, New Brunswick, Canada	just pre-1800	1850 -1880