Identifying sediment discontinuities and solving dating puzzles using monitoring and palaeolimnological records

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Abstract Palaeolimnological studies should ideally be based upon continuous, undisturbed sediment sequences with reliable chronologies. However for some lake cores, these conditions are not met and palaeolimnologists are often faced with dating puzzles caused by sediment disturbances in the past. This study chooses Esthwaite Water from England to illustrate how to identify sedimentation discontinuities in lake cores and how chronologies can be established for imperfect cores by correlation of key sediment signatures in parallel core records and with long-term monitoring data (1945–2003). Replicated short cores (ESTH1, ESTH7, and ESTH8) were collected and subjected to loss-on-ignition, radiometric dating (^{210}Pb, ^{137}Cs, and ^{14}C), particle size, trace metal, and fossil diatom analysis. Both a slumping and a hiatus event were detected in ESTH7 based on comparisons made between the cores and the long-term diatom data. Ordination analysis suggested that the slumped material in ESTH7 originated from sediment deposited around 1805–1880 AD. Further, it was inferred that the hiatus resulted in a loss of sediment deposited from 1870 to 1970 AD. Given the existence of three superior ^{14}C dates in ESTH7, ESTH1 and ESTH7 were temporally correlated by multiple palaeolimnological proxies for age-depth model development. High variability in sedimentation rates was evident, but good agreement across the various palaeolimnological proxies indicated coherence in sediment processes within the coring area. Differences in sedimentation rates most likely resulted from the natural morphology of the lake basin. Our study suggests that caution is required in selecting suitable coring sites for palaeolimnological studies of small, relatively deep lakes and that proximity to steep slopes should be avoided wherever possible. Nevertheless, in some cases, comparisons between a range of contemporary and palaeolimnological records can be employed to diagnose sediment disturbances and establish a chronology.

Keywords sediment disturbance, lake sediment, chronology, slumping, hiatus, Esthwaite Water

1 Introduction

In recent decades, palaeolimnological research has developed significantly and has played an important role in developing our understanding of environmental change over a variety of spatial and temporal scales (Cohen, 2003; Smol, 2008). A sound piece of palaeolimnological research requires good materials (such as undisturbed lacustrine sediment and well-preserved fossils), high quality analytical methods (including laboratory protocols and data analysis methods), and a reliable chronology (Birks and Birks, 2006). In particular, a well resolved chronology is important to the increasing number of studies which synthesize core data from multiple individual palaeolimnological investigations to make environmental change inferences at regional and global scales (Sadler, 2004). For example, the generation of precise and accurate chronologies for core sequences is a key prerequisite for comparing proxy records of past climate change between hemispheres (Blockley et al., 2008). Additionally, it is only possible for palaeolimnologists to determine rates of processes and fluxes of materials, and to correlate the abrupt nature of past climate change or other historical events with sediment archives, if reliable chronologies are established (Birks and Birks, 2006; Rasmussen et al., 2006).

Great progress has been made in resolving sediment core chronologies over the past three decades. Several data sources, such as algal records (Haworth, 1980) and pollen (Yeloff and Mauquoy, 2006), spheroidal carbonaceous particle (Rose et al., 1995) and tephra (Lowe, 2008) profiles in cores have been used to validate chronological models based on radiometric data. Much palaeolimnological work has been undertaken at high temporal resolution by studying annually laminated sediment records (e.g., Renberg, 1981; Chu et al., 2005; Besonen et al., 2008) or by sampling cores at fine intervals using improved corers and core extruding systems (Glew, 1988). In addition, several statistical approaches have been developed for establishing and refining age-depth models (Bennett and Fuller, 2002; Telford et al., 2004; Heegaard et al., 2005; Sanchez-Cabeza and Ruiz-Fernández, 2012).

It is relatively common to encounter disturbed sediment cores due to external (flood, hurricane, or sediment dredging) and internal (e.g. sediment mixing, slope failure, bioturbation) disturbances. For example, in lowland and floodplain areas, lake sediment may be disturbed easily by frequent flooding events and/or from increasing human impact, including lake restoration, fishery, reclamation, and even dredging. As a consequence, lake sediments can sometimes suffer from non-constant accumulation rates, slumping events, and hiatuses, which may lead to complex and incomplete core records and thus misinterpretation (Håkanson and Jansson, 1983; Larsen and MacDonald, 1993; Bangs et al., 2000, Gilbert and Lamoureux, 2004; Martin et al., 2005). For that reason, most disturbed sediment cores are often abandoned and are not used for further analysis. This is the best strategy when the disturbance can easily be detected. However, not all is lost and sometimes, with a degree of detective work, sediment disturbances can be identified and understood. In turn, information on sedimentation processes may allow for inferences of key environment changes in the past, e.g. floods, earthquakes, fire, or human reclamation events (Arnaud et al., 2002; Moreno et al., 2008) and although sediment disturbances can be disadvantageous, numerous palaeolimnological studies have revealed that a reasonable chronology can be achieved, especially where multi-core comparisons allow sediment disturbances to be distinguished (Tibby 2001; Donovan and Grimm, 2007; Morellón et al., 2011).

In this study, data from a disturbed sediment core collected from a small UK lake (Esthwaite Water, English Lake District) is presented and the procedure for identifying disturbances of the core and for establishing a chronology is illustrated. Comparisons are made between multiple sediment proxies (including loss-on-ignition, sediment particle size, diatoms, and metals) in both the disturbed sediment core (ESTH7) and in two other dated sediment cores (ESTH1 and ESTH8). Furthermore, long-term monitoring data for planktonic diatom data (covering a period of 59 years) are used to help date key floristic changes in the cores. Using these data, we aim to: i) identify the occurrence and timing of disturbance events (slumping and hiatus) in core ESTH7; ii) develop a reliable age-depth relationship for the lake by combining existing ^{210}Pb and ^{14}C dating results; and iii) evaluate sedimentation variability in the lake and possible causes for the two identified sediment disturbances.

2 Methods

2.1 Study site

Esthwaite Water (54°21.56'N, 02°59.15'W) is located in the English Lake District. It is a small lake with a surface area of 1 km^2 and mean and maximum depths of 6.9 m and 16 m, respectively. The lake has a contorted shore line and a rough lake bottom (Mackay et al., 2012). There are five major inflow streams, four of which have inlets within 400 m of the deepest point of the lake (Fig. 1). The lake receives high annual rainfall, reaching an average of 1,900 mm per year. It has a moderate alkalinity (0.4 mequiv/L) and is currently is eutrophic (21 μg/L and 630 μg/L for average TP and maximum winter NO_3-N, respectively) and typically remains thermally stratified from the end of April to the middle of October (Maberly and Elliott, 2012).

The lake has received considerable attention from limnologists in the past century and has been the subject of numerous contemporary ecological and palaeolimnological studies. A monitoring programme, starting at Esthwaite Water in the early 1940s, provides long-term data for various chemical and biological variables (Maberly and Elliott, 2012). Additionally, a number of contemporary and palaeo- limnological studies have been undertaken at the site (see review in Bennion et al., 2000; George, 2012). Dong et al. (2012) reported the complex interactions between climate and nutrients over a 1,200 year timescale by means of a multiproxy sediment core study in this lake.

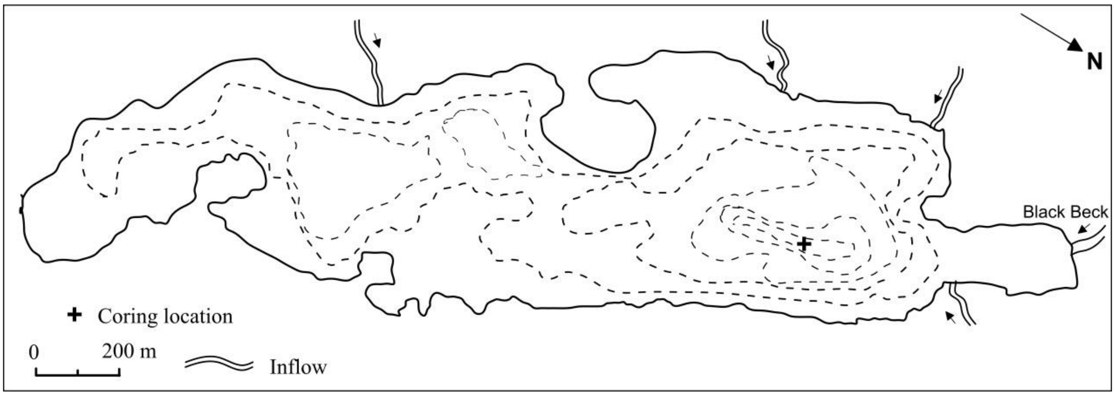

Fig. 1 Location and bathymetric map (unit: meters) of Esthwaite Water, English Lake District, showing the coring location of the three cores.

2.2 Field sampling

Phytoplankton samples have been collected from the deepest part of Esthwaite Water since 1943, initially by Freshwater Biology Association (FBA) and since 1989 by the Centre of Ecology and Hydrology, generally on a fortnightly-monthly basis (Maberly and Elliott, 2012). Integrated surface water samples (0–5 m) were collected using a weighted plastic tube and preserved with Lugol's iodine for further lab analysis.

The three sediment cores utilised in this study were all collected from the deepest part of the lake at the same location (54°21'47"N, 2°59'08"W; Fig. 1) as follows: (i) ESTH1 – a 86 cm core taken using a mini-Mackereth piston corer (Mackereth, 1969) on 7 June 1995 and sliced at 0.5 cm (upper 30 cm) and 1.0 cm (below 30 cm) intervals; (ii) ESTH7 – a 65.5 cm core taken using a percussion piston corer (Chambers and Cameron, 2001) on 12 April 2006 and sliced at 0.25 cm (upper 20 cm) and 0.5 cm (below 20 cm) intervals; and (iii) ESTH8 – a 31 cm core taken using a mini-Mackereth piston corer on 15 August 2007 and sliced at 0.5 cm intervals throughout. By taking replicated sediment cores from the same location, it is possible to examine the coherence among the sediment sequences.

2.3 Laboratory methods

Sediment samples from Esthwaite Water cores ESTH7 and ESTH8 were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs, and ^{241}Am by direct gamma assay at University College London, using an ORTEC HPGe GWL series well-type coaxial low background intrinsic germanium detector. ^{210}Pb was determined via its gamma emissions at 46.5keV, and ^{226}Ra by the 295keV and 352keV gamma rays emitted by its daughter isotope ^{214}Pb following three weeks storage in sealed containers to allow radioactive equilibration. ^{137}Cs and ^{241}Am were measured by their emissions at 662keV and 59.5keV respectively. The absolute efficiencies of the detector were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self absorption of low energy gamma rays within the sample. ^{210}Pb chronologies were calculated using the constant rate of supply (CRS) model (Appleby and Oldfield, 1978). The same radiometric methods were applied to core ESTH1 at the University of Liverpool in 1995.

Three radiocarbon dates were determined from leaf fragments of *Alnus glutinosa* from three ESTH7 sediment samples (depths of 47.25–47.5 cm, 59.25–59.75 cm, and 63.25–63.75 cm) using Accelerator Mass Spectrometry (AMS). The corresponding dates were calibrated to 636 ± 50 BP, 1075 ± 100 BP and 1160 ± 110 BP for samples at the above levels, respectively. See more details in Dong et al. (2012).

Methods used for the analysis of the different proxies, including loss-on-ignition (LOI), particle size, and trace metal (including Al, Ba, Be, Ca, Co, Cr, Cu, Fe, Mn, Na, Ni, P, Pb, Sr, Ti, V, Zn, K, Mg) are described in Dong et al. (2012). Median particle size (MD) was calculated as a measure of the central tendency of the different particle size distributions.

In the laboratory, planktonic diatom compositions were determined for a sub-sample of the preserved samples using an inverted microscope (Lund et al., 1958). In this study annual average percentages for each species were calculated and only the diatom component of the dataset was used. Microscope slides for sedimentary diatom analysis were prepared using standard techniques (Battarbee et al., 2001). All samples were mounted on microscope slides using Naphrax and were observed under light microscopy at ×1000 magnification. Diatom taxonomy mainly followed Krammer and Lange-Bertalot, 1986–1991. Diatom data are presented as relative abundances. Owing to difficulties with discerning small centric species (less than 10 μm in diameter) in the plankton samples using inverted microscopy, their sum was calculated as "small *Stephanodiscus/Cyclotella* spp." for comparison with the sediment records.

2.4 Core correlation, sediment continuity assessment, and age model development

Cores ESTH1 and ESTH7 have overlapping lengths and time ranges and were used for most of the inter-core correlation. Core ESTH8 (31 cm in length) is much shorter than core ESTH7 and therefore only radiometric and LOI data were analyzed and used for comparison purposes. Two approaches were used to assess the continuity of sedimentary processes in core ESTH7. Firstly, palaeolimnological proxies including LOI, particle size, trace metal concentration, and diatom composition were correlated between cores ESTH7 and ESTH1 using a "wiggle-matching" approach (Anderson, 1986). Secondly, major species from the 59-year monitoring record of planktonic diatoms were compared with the diatom records in both sediment cores. Additionally, Principal Component Analysis (PCA) was employed using data common to both cores (LOI, particle size, geochemical data, and diatom composition) to reveal the similarity among samples in core ESTH7. The sedimentary data from core ESTH7 were square-rooted or log transformed to achieve a normal distribution prior to PCA ordination. To decrease the colinearity within the element data, the PCA scores of the first two axes based on each group of proxies were used for the final PCA analysis. Samples lying in close proximity in PCA ordination space are likely to have similar compositional characteristics (ter Braak and Smilauer, 2002). Theoretically, therefore, this method can be used to track abrupt changes or inconsistencies in cores that might arise from slumping or hiatus events. PCA was performed using the software package Canoco for Windows, version 4.5 (ter Braak and Smilauer, 2002).

Based on the ^{210}Pb chronologies, ^{14}C dating, and the correlated points in cores ESTH1 and ESTH7, sediment accumulation rates were calculated and compared. Given the continuous sedimentation and higher sediment accumulation rates for ESTH1, the three ^{14}C dates derived for ESTH7 were assigned to the corresponding levels of ESTH1 according to the established core correlation. The latter core was subsequently used for developing and refining an age-depth model. Based on a fixed ratio of 1:2 between the sediment accumulation rates of the two cores (Table 1), core ESTH1 was extended to a length of 97.5 cm, since its original length did not extend back to the two earlier ^{14}C dates (1075 BP and 1160 BP, see below).

Finally, a new integrated record, ESTH9, including the top 8.5 cm of ESTH7 (representing the period 1993–2006 AD), the top 30 cm of ESTH1 (representing the period 1880–1993 AD) and 28.5–65.5 cm in ESTH7 (representing the period 780–1880 AD), was derived. This chronology has been used in a millennial-scale study of climate and nutrient impacts on the lake (Dong et al., 2012).

3 Results

3.1 Radiometric analysis

Unsupported ^{210}Pb activity in ESTH1, excluding samples from the surface and at a depth of 15 cm, exhibits a reasonable exponential decay with depth (Fig. 2(a)). The ^{137}Cs measurements identify a major peak in activity at 5.25 ± 2.5 cm likely recording fallout from the 1986 Chernobyl accident. This corroborates the CRS model ^{210}Pb dates which places 1986 at ~6 cm. Although the deeper ^{137}Cs measurements were insufficient to resolve the 1963 fallout peak with any accuracy, the ^{241}Am record suggests that this feature occurs at 11.5 ± 2 cm, in reasonable agreement with the ^{210}Pb determined level of 1963 at 14 cm (Fig. 2(b)).

In ESTH7, unsupported ^{210}Pb activity declines irregularly with depth (Fig. 2(d)). There is little net reduction in ^{210}Pb activity over the uppermost 15 cm, but there is a sharp decline in the section at 9–13 cm. Unsupported ^{210}Pb activity declines rapidly from 105.5 to 8.7 Bq/kg over the depth range 24.75–26.25 cm, suggesting discontinuous sedimentation or a substantially changed sedimentation environment in this section. The ^{137}Cs activity versus depth profile shows a similar pattern to ^{210}Pb with abrupt decreases at 9–13 cm and 24–26 cm (Fig. 2(e)). ^{241}Am was detected in samples from 15.88 cm, 20.25 cm, and 22.13 cm, although concentrations were insufficient to resolve the 1963 fallout maximum.

Unsupported ^{210}Pb activity in core ESTH8 also declines irregularly with depth (Fig. 2(g)). There is little net decline in top 8 cm and section 13–20 cm, suggesting that there is an increase in sediment accumulation in these individual sections. The ^{137}Cs activity versus depth profile shows a well-resolved peak at 15.75 cm and a less well-resolved wide peak centred on 25.75 cm, which are assumed to represent the 1986 Chernobyl accident and the 1963 fallout maximum from atmospheric weapons, testing respectively. The latter feature is confirmed by detectable ^{241}Am (Fig. 2(h)).

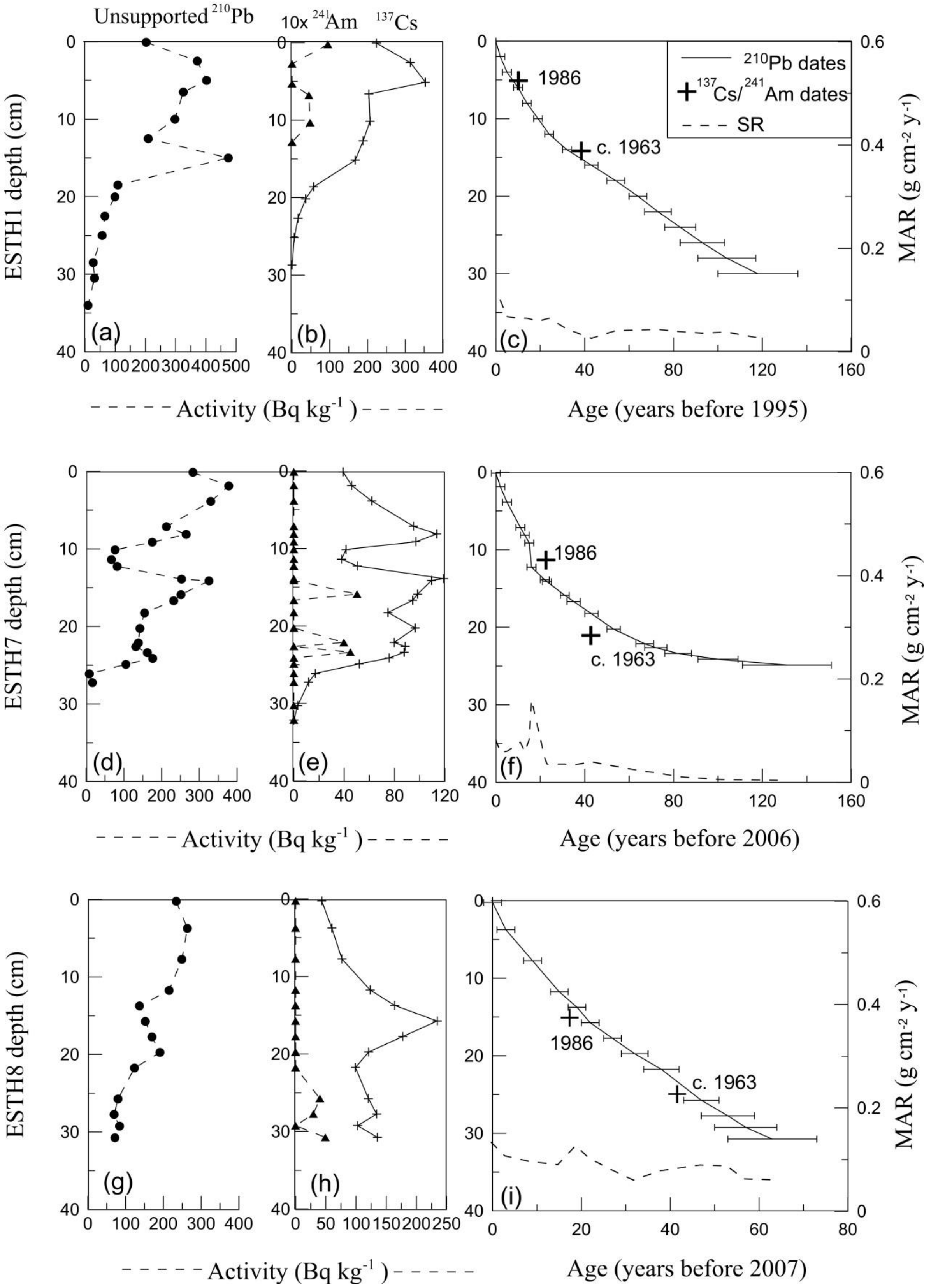

Fig. 2 Fallout radionuclide concentrations and age-depth relationships of cores ESTH1 ((a)–(c)), ESTH7 ((d)–(f)), and ESTH8 ((g)–(i)).

Given variable sediment accumulation rates in the lake, ^{210}Pb chronologies were calculated using the constant rate of ^{210}Pb supply (CRS) model for all cores. In ESTH1, mean mass accumulation rates are relatively stable with an average of 0.038 g cm^{-2} y^{-1} prior to the 1960s, compared with higher values of ~0.062 g cm^{-2} y^{-1} after the 1960s (Fig. 2(c)). For ESTH8, mass accumulation rates also exhibit a major change in the 1960s, but are higher than ESTH1: 0.075 g cm^{-2} y^{-1} and 0.097 g cm^{-2} y^{-1}, average accumulation rates before and after the 1960s, respectively (Fig. 2(i)). For ESTH7, ^{210}Pb data from the upper 8 cm of the core were used to ascribe dates due to the discontinuities described above. These are discussed further below.

3.2 Comparison of LOI and particle size profiles

The LOI profiles of ESTH7, ESTH8, and ESTH1 match well (Fig. 3(a)), suggesting good potential for core correlation. LOI values in cores ESTH7 and ESTH8 match well in depths due to small difference (<2 years) in coring dates. Particle size profiles also show similar trends (Fig. 3(b)), although the link is not quite as clear. Several peaks and troughs were linked across the two cores by the “wiggle-matching” method. However, one feature that stands out as different in ESTH7 is an abrupt decrease in LOI values within the section 9.5–13 cm (as marked in Fig. 3(a)). The average LOI for this section is 21.9%, significantly lower than the values in neighbouring layers, all of which are over 23.5%. This sharp decrease is consistent with the occurrence of a slumping event (see below discussion) as the decline in LOI values is not seen in ESTH1. It is also coincident with the sharp declines observed in the radiometric activities of ^{210}Pb and ^{137}Cs in this section of the core (Fig. 2(d) and 1(e)).

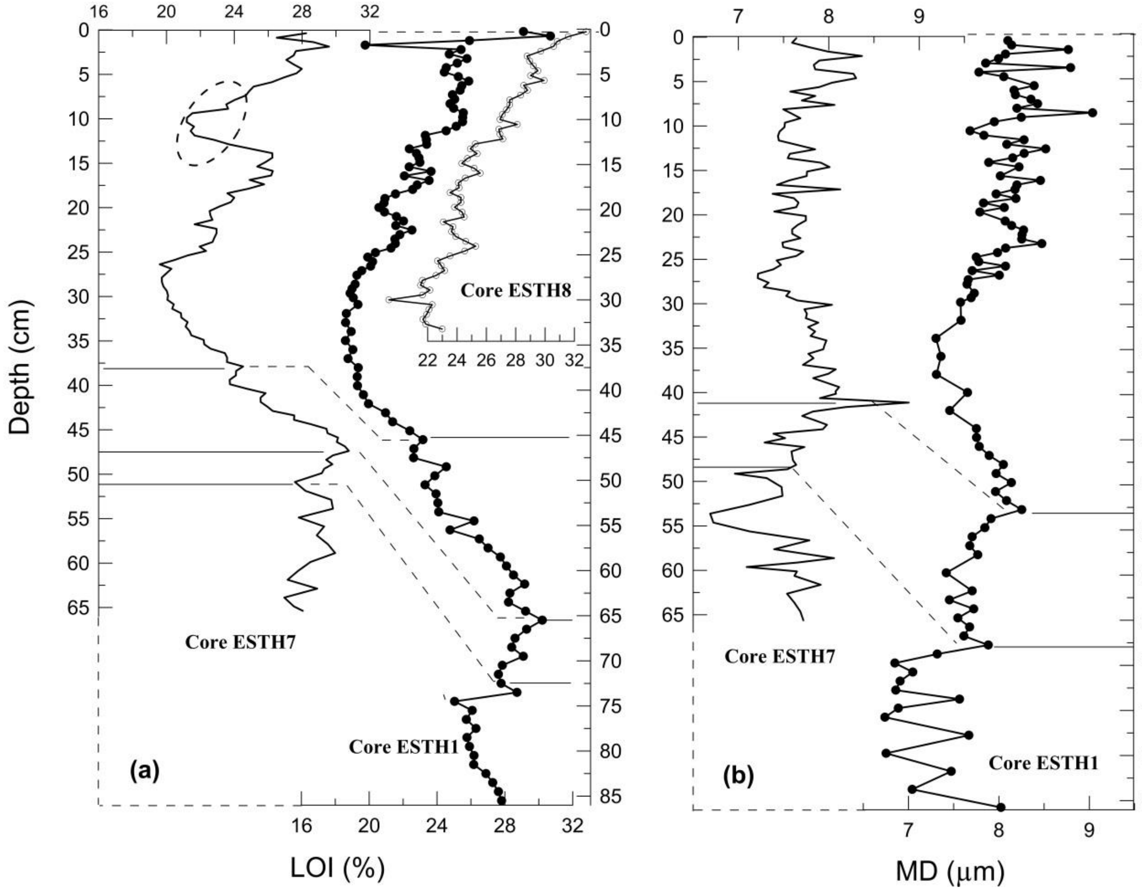

Fig. 3 Core correlation (a) organic matter (%LOI) among cores ESTH1, ESTH7, and ESTH8; and (b) median particle size (MD) for cores ESTH1 and ESTH7. The dashed lines and dashed circle indicate correlative features between the two cores and the slumping event, respectively.

3.3 Comparison of metal concentrations

Vertical profiles of several selected metals and ratios of Mg/Ca and Fe/Mg in cores ESTH1 and ESTH7 are given in Fig. 4. Their distributions all have sharp peaks or valleys that are conducive to inter-comparison and four corresponding features were identified: 1) peaks in Co, Ni, and Ba at depths of 69.5 cm and 49.5 cm in ESTH1 and

ESTH7, respectively; 2) a peak in Fe, along with reductions in Ba, Cr, Ni, and Mn, at depths of 63.5 cm and 46.5 cm in ESTH1 and ESTH7, respectively; 3) dips in concentrations of Cr, Ni, and Mg/Ca at depths of 45.5 cm and 38 cm in ESTH1 and ESTH7, respectively; 4) abrupt changes in concentrations of Cr, Ni, Mn, Mg/Ca, and Fe/Mg at depths of 30 cm and 28.5 cm in ESTH1 and ESTH7, respectively.

In addition to similarities in the elemental data, coherence of sediment accumulation rates was also evident in the lower part of the two cores (below 45.5 cm in ESTH1 and 38 cm in ESTH7). The depths of sediment between correlative features 1 and 2, and 2 and 3, were 6 cm and 18 cm respectively in ESTH1 and 3 cm and 9 cm, respectively in ESTH7 (Fig. 4). These data, exhibiting a fixed ratio of 1:2 between the age-depth relationship in the two cores, indicate that the sedimentation rate of ESTH1 was twice that of ESTH7.

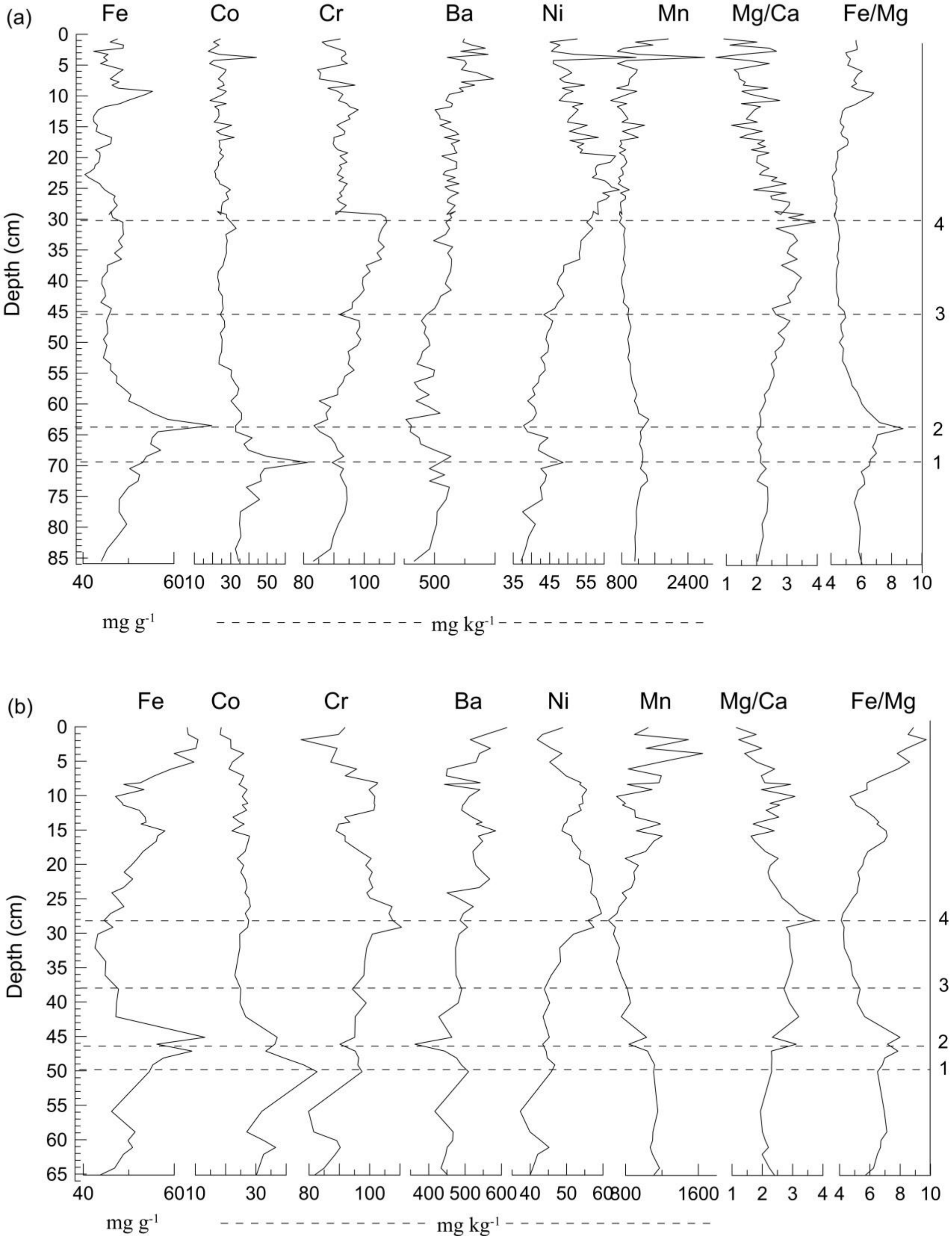

Fig. 4 Selected metal concentration profiles for cores ESTH1 (a) and ESTH7 (b). Dashed lines indicate correlative features 1, 2, 3, and 4 (also see Table 1).

3.4 Comparison of diatom profiles and plankton monitoring data

The fossil diatoms in ESTH7 exhibit two major compositional shifts (Fig. 5). Below ~60 cm, assemblages were dominated by *Aulacoseira subarctica*, above which this taxon exhibited a marked decline and *Cyclotella comensis* increased. The second major shift occurred at ~26 cm when *C. comensis* decreased and there was an expansion of taxa associated with more eutrophic waters, especially *Asterionella formosa*, *Fragilaria crotonensis* and *Stephanodiscus binatus*. In ESTH1, there was only one distinct shift at ~25 cm (~1905 AD according to the ^{210}Pb dating), similar to that at ~26 cm in ESTH7 with a shift in dominance from of *C. comensis* to *A. formosa* and *F. crotonensis*. The earlier shift was not observed in ESTH1 most likely because this core covers a shorter time interval.

Two clear discrepancies could be observed in the diatom stratigraphies of the two cores (Fig. 5). Firstly, the high percentages of *F. crotonensis* and *S. binatus* were almost synchronous in ESTH7, but in ESTH1 *S. binatus* appeared about seventy years later than *F. crotonensis* (a difference of 14 cm in terms of sediment depth). Secondly, there was a resurgence of *C. comensis,* and *Cyclotella radiosa* at the depth 9.5–13 cm in ESTH7, but in ESTH1 no such shift was observed and diatom assemblages were dominated by *F. crotonensis* and *S. binatus* throughout the upper part of the core.

Planktonic monitoring data (Fig. 5) reveal that small (<10 µm) *Stephanodiscus* and *Cyclotella* taxa started to appear in the lake at relatively high percentages from 1975. This change was well reflected in ESTH1 in which *S. binatus* occurred from 11 cm, dated to 1973 AD. Further, a short-lived peak in *Aulacoseira granulata* var. *angustissima* occurred in 1999–2002 according to the monitoring record. This was well documented in ESTH7 at a depth of around 6 cm (^{210}Pb dated to 1999 AD). These two distinctive shifts in species composition provide further assistance with correlating the two cores.

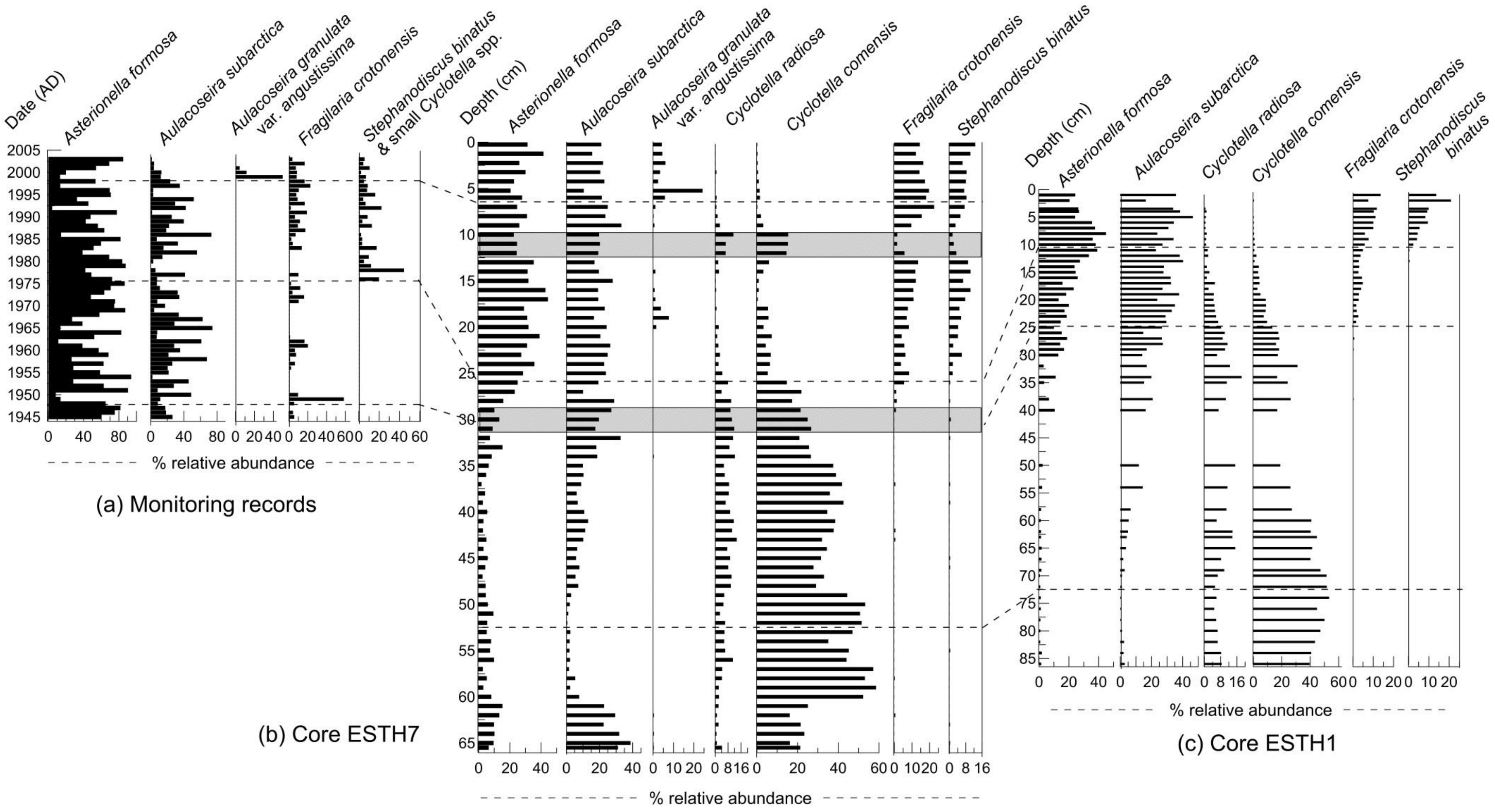

Fig. 5 Relative abundance data of selected dominant diatom species from (a) monitoring records, (b) core ESTH7, and (c) ESTH1. Core correlations as outlined in the text are marked by dotted lines. The shadows around depths of 10 and 30 cm in ESTH7 indicate the slumping and hiatus events, respectively.

3.5 Comparison of multiple sediment proxies

PCA of all the sedimentary proxies reveals that samples during the suspected slumping period (samples 12–15, representing the depth 10–12.5 cm) are most similar to those which were older than 1900 AD (Fig. 6). The seven samples (samples 28, 30, 31, 32, 33, 52, 53), located in the selected “sample distance” circle, are closest to the “slumping” samples (Fig. 6). Excluding the two very old samples (samples 52 and 53), the remaining five samples were all deposited during 1805–1880 AD, suggesting that sediment in the “slumping” samples originated from material deposited during this era.

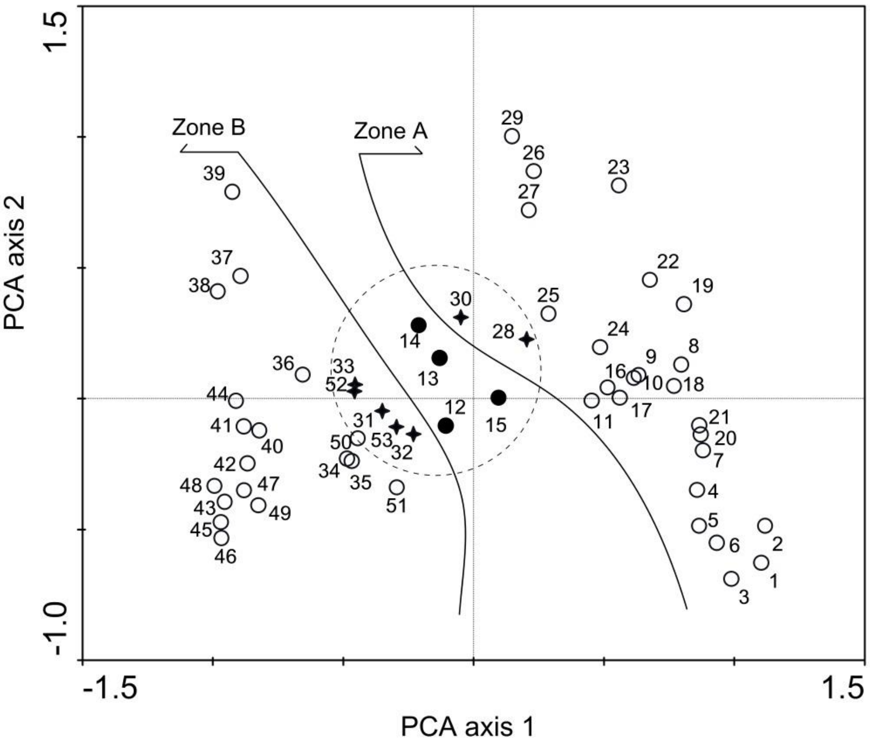

Fig. 6 Principle component analysis (PCA) of all the proxy data, including LOI, particle size, geochemical data, and diatom composition. Zones A and B show the samples younger or older than the 1900s, respectively. Samples 12–15 (solid circle, representing the slumping samples from the depth 10–12.5 cm) and the most similar samples (filled star) are shown in the dashed circle.

3.6 Core correlation and chronology development for core ESTH7

The multi-proxy comparison conducted above has revealed several points of high temporal correlation between cores ESTH1 and ESTH7. As mentioned above, the depths of corresponding layers in the two cores exhibited a fixed ratio of 1:2, indicating that sediment accumulation rates in ESTH1 were twice as high as those in ESTH7. Using this information in combination with the ^{210}Pb and ^{14}C dating, dates were calculated for each point of correlation by interpolation or extrapolation (Table 1).

Table 1 Temporal relationship between sediment cores ESTH1 and ESTH7

Depth in ESTH7/cm	Depth in ESTH1 /cm	Evidence or by core correlation	Inferred dates by core correlation (AD)
5.25	/	Appearance of high percentages of *A. granulata* var. *angustissima*	1999$^{1)}$
14–26	0–11	Increase in *S. binatus*	Post-1970
28.5	30	Mg/Ca, Cr, Ni, Mn	1877$^{2)}$
38	45.5	LOI, Cr, Mg/Fe, Ca	1630$^{3)}$
41	53	Particle Size	1550$^{3)}$
46.5	63.5	Fe, Cr, Ba, Mn, Fe/Mg	1406$^{3)}$

47.5	65.5	LOI, Particle Size	1380[4]
49.5	69.5	Ba, Ni, Co	1250[3]
51	72.5	LOI, diatoms	1180[3]
59.5	89.5[5]	/	930[4]
63.5	97.5[5]	/	840[4]

1) Based on ^{210}Pb dating of ESTH7 and plankton monitoring data; 2) Based on ^{210}Pb dating of ESTH1; 3) Interpolated dates using average sediment accumulation rates; 4) Results from calibrated ^{14}C dating; 5) Extrapolated depth according to the sediment accumulation rate relationship between the two cores.

A slumping and a hiatus event in ESTH7 were clearly revealed by the core cross-comparisons. At around 11 cm in ESTH7, the diatom records (abrupt high abundances of *C. comensis*, *C. radiosa*, *A. minutissima*), radiometric elements (the sudden decrease of ^{210}Pb and ^{137}Cs activity), and LOI data (large dip in values) indicated that a slumping of old material occurred at around 1990 AD. Furthermore, a hiatus at around 26 cm in ESTH7 was indicated by the rapid, anomalous disappearance of *F. crotonensis*, which should not be synchronous with the disappearance of *S. binatus* in the early 1970s (Fig. 5). By linking metal concentration profiles for cores ESTH1 and ESTH7, the depth of 28.5 cm in core ESTH7 is corresponding to 30cm in core ESTH, which is dated to 1877 AD by ^{210}Pb data (Fig. 2 and Table 1). Consequently, the hiatus appears to have resulted in a sediment loss covering more than 100 years.

The final age-depth relationship was established using ^{210}Pb data for ESTH1 and the three ^{14}C dates for ESTH7 (Table 1). Given the inherent error of the age-depth model based on ^{210}Pb, ^{137}Cs, and ^{14}C, all ages used in this paper are approximate. The time-scale discussed here extends back to 780 AD.

4 Discussion

Multi-proxy comparison of cores ESTH1, ESTH7, and ESTH8 from Esthwaite Water indicated that both a slumping and a hiatus event were evident in ESTH7. All of the cores were taken from the deep central area of the lake (Fig. 1). In general, the deepest area of a lake receives most sediment mass through the process of sediment focusing and often sediment accumulation rates tend to be higher than found in littoral regions (Håkanson and Jansson, 1983; Cohen, 2003; Smol, 2008). Despite differences in sediment accumulation rates across cores, even in small lakes, it is usually possible to match profiles for various sediment signatures (e.g., LOI, diatom community shifts) so that chronologies can be transferred between cores (Anderson et al., 1994; Barker et al., 2005). Indeed, in Esthwaite Water, existing palaeolimnological data from several cores (ESTH1-ESTH8) taken over the last 15 years exhibit close matches in LOI and diatom stratigraphies (Bennion, unpublished data). However, in an earlier palaeolimnological study undertaken by Sanders et al. (1992), there was evidence for various mechanisms that may disrupt the sediment record in Esthwaite Water, namely, a broad Chernobyl ^{137}Cs peak and an earlier peak in polychlorinated biphenyls (PCB) fluxes than might be expected based on UK production dates. In this study, Sanders et al. (1992) concluded that post-depositional changes had occurred due to vertical sediment mixing processes (e.g., bioturbation and molecular diffusion). Hence palaeolimnological records from Esthwaite Water are clearly prone to disturbance.

PCA ordination (Fig. 6) based on all the sediment signatures in ESTH7 positioned the slumping samples alongside samples deposited between 1805–1880 AD (corresponding depth of 24.25–28.25 in ESTH7). Further, the slumping event occurred at around 1990, according to the inter-core comparison. Given relatively high percentages of the eutrophic diatom species *Stephanodiscus binatus*, the 24.25–28.25 cm layer should date to post-1970 AD as this species was not observed in the lake plankton until this time (Fig. 5). Correlation of cores ESTH1 and ESTH7 suggests that this layer was dated to 1877 AD. The difference between the two dates indicates that a period of *c.a.* 100 years (1870–1970 AD) is missing from the sediment record of ESTH7.

There are several possible reasons for the discontinuities observed in ESTH7. Firstly, given the small size of the lake and the steep sloping nature of the basin in the coring area, occasional sediment slumping events are likely (Larsen and MacDonald, 1993). For example, a study of a small lake (25 ha) in New York, USA, revealed that approximately 50% of the material deposited in the main basin was slumped material derived from basin slopes (Ludlam, 1974). Additionally, Bennett (1986) found several slumping-derived deposits in a small lake in Ontario, Canada, with an average slope of 5 °. In Esthwaite Water, slope measurements range from 1 ° to 13 °, with higher values near the central area (Fig. 1 and Mackay et al., 2012). This relatively steep slope may result in sediment focusing and thus an increased possibility of slumping in this region, which is close to the main inflow to the lake at Black Beck (Fig. 1). Secondly, Esthwaite Water is a small lake that has been the subject of several palaeolimnological studies. Numerous sediment cores have been extracted from the lake, mostly from the deepest area (see review in Bennion et al., 2000). Coring work can potentially disturb sediments and this possibility should not be ignored. Thirdly, incorrect or careless sampling can result in sediment discontinuities. For example, lowering the core too quickly may reduce compression but contribute to sediment loss (Baxter et al., 1981). However, this is unlikely to be a factor in explaining the disturbed record of ESTH7.

Sedimentation rates in Esthwaite Water exhibit high spatial variability within the relatively small coring area (coring points may be slightly different, even coring from the same coordination from GPS). Indeed the sediment accumulation rates of ESTH1 and ESTH8 are twice and four times as high as those in core ESTH7, respectively. Whilst there are many studies comparing sediment processes for multiple cores from a single basin (e.g., Anderson et al., 1994; Rose et al., 1995; Tibby, 2001), it is seldom the case that large differences in sedimentation rates are reported for cores taken from the same area of a lake. This is probably due to the uneven, slim foot-print shape of the deep basin in this lake (Fig. 1). Nevertheless, given the good agreement in sediment signature shifts across cores from different parts of Esthwaite Water, it is clear that such variability in sediment accumulation rates does not necessarily limit palaeolimnological reconstructions.

An effective solution for defining and coping with disturbed sediment cores is illustrated in this study. A range of contemporary and palaeolimnological records, including existing monitoring data, sediment stratigraphy, episodic events, and other anthropogenic time markers can all provide valuable information to aid our understanding of past physical limnological and sedimentation processes. Even if there are no monitoring records for sequence validation, this study revealed that some key features in cores can be found to warn and diagnose sediment discontinuities in other records. Such features includes the "re-dominance" of certain species (such as oligotrophic species *C. comensis*) after the lake became enriched and abrupt changes in sedimentary physico-chemical properties (e.g. sudden decrease in LOI or permanent organic pollution). In cases with no or limited limnological records, known catchment events such as the occurrence of flooding, large scale fire, migration of local people, or volcanic eruption, can be used to gauge the reliability of the sediment sequence. Meanwhile, dating of cores via inter-core correlation can be widely and effectively employed. In particular, some low-cost and less time consuming methods, such as magnetic susceptibility or other core scanning methods (e.g., X-ray fluorescence), are favourable in such core correlations.

We acknowledge that the sedimentation discontinuities of Esthwaite Water sediment cores are site-specific to some extent, given the small lake basin and complex lake shore with sharp slopes. However, the slumping and hiatus may occur frequently in many lakes for those sharing similar lake morphology as Esthwaite Water, or lakes from regions with strong human impact and climate change (cf. Anderson, 2014; Drzymulska and Zieliński, 2014). In most of those situations, the pre-examined sediment cores are likely to have been abandoned and not used for further analysis, resulting in a relatively small number of published reports based on disturbed sediment records. In contrast, the current study presents a strong cautionary tale on how to adapt to sediment discontinuities and extract adequate information on environmental change even from imperfect cores.

5 Conclusions

This study revealed how it is possible to use monitoring and palaeolimnological records to assess the integrity of sedimentation and solve dating puzzles. Using the “wiggle-matching” method, sedimentary proxies in cores ESTH1 and ESTH7 were correlated and a slumping and a hiatus event were detected in core ESTH7. PCA ordination based on the sedimentary proxies revealed that the slumping material in the core originated from sediment deposited around 1805–1880 AD. The hiatus resulted in the loss of *c.a.* 100 years of material, from 1870 to 1970, according to the inferred dates. This study demonstrates that considerable heterogeneity in sediment accumulation rates can occur in the deep basins of relatively small lakes. Consequently, care is needed when selecting coring sites for palaeolimnological studies from such lakes. We propose that a multi-proxy approach based on inter-comparisons between cores can be employed to diagnose sediment disturbances and establish a chronology.

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