Holocene sediment dynamics in an upland temperate lake catchment: climatic and land-use impacts.

Robert G. Hatfield and Barbara A. Maher

Centre for Environmental Magnetism and Palaeomagnetism, Lancaster Environment Centre, Department of Geography, University of Lancaster, LA1 4YQ, UK

Email: b.maher@lancaster.ac.uk; r.hatfield@lancaster.ac.uk
Phone: +44 (0)1524 510268
Fax: +44 (0)1524 510269

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Abstract

Accelerated erosion and transport of fine sediment from upland temperate catchments can reflect increased erosivity and/or erodibility, due in turn to climatic and/or human forcing. Identification of sediment fluxes and sources over Holocene timescales can both enable understanding of the relative impacts of these forcings, and provide perspective on recent sediment fluxes. Here we present a ~ 5,500 year record of sediment fluxes and sources from Lake Bassenthwaite utilising magnetic measurements and fuzzy clustering, coupled with independent pollen and archaeological records, to identify the timing and impact of catchment disturbance. This record shows that recent sediment flux increases (i.e., within the last 150 years) are unprecedented in scale throughout the mid-late Holocene and appear to be in response to specific human changes occurring within the catchment. Earlier episodes of human activity, from the mid-Holocene onwards, show no link with increased lake sediment fluxes, indicating either limited catchment impact and/or 'buffering' through within-catchment sediment storage. Increasingly intensive land use and reduction of sediment storage through revetment construction on a key inflow, Newlands Beck, have resulted in 3 x increases in lake sediment flux. These data may be significant for other upland temperate areas, as increasing land use pressures and reduced sediment storage capacity may not only increase contemporary sediment flux, but increase sensitivity to predicted increases in rainfall and storminess as a result of global warming.

Introduction

Lake sediment sequences often comprise important, continuous, natural archives, enabling reconstruction of past catchment processes and changes in climatic and environmental conditions. For Holocene sequences, identification of the history of sediment fluxes and sources is a key requirement for evaluating the relative roles of climate- and human-induced forcings in lake sedimentation processes. Additionally, if the historical and prehistorical context for modern, often accelerated sediment fluxes can be established, the requirement for and scale of possible mitigation measures can also be addressed. Key requirements for studies of lake sediments and flux rates over millennial timescales include robust chronological control, most often sought by radiometric means, especially ^{210}Pb and ^{14}C (Libby, 1955; Nelson et al., 1977; Appleby and Oldfield 1978; Oldfield at el., 1980; Oldfield & Appleby, 1984; Oldfield et al., 1997), supplemented by indirect dating proxies, such as palaeomagnetic secular variation (PSV, Turner & Thompson, 1981; Sagnotti et al., 2005), pollen analysis (von Post 1946; Pearsall and Pennington, 1947; Birks, 1986), and pollution particles (Locke & Bertine, 1986; Rose & Appleby 2005). Identification of the sources of lake sediments, and possible changes in sediment provenance through time, has been attempted using a diverse range of sediment 'fingerprinting' techniques (e.g. Walling et al., 1979; Oldfield et al., 1985; Foster & Walling, 1994; Collins and Walling 2002; Bradshaw & Thompson, 1985; Walden et al., 1997; Kodama et al., 1997; Hatfield & Maher, 2008). In addition to information characterising the properties of the inorganic components of lake sediments, palynological analysis can provide an independent overview of changing lake catchment conditions.

Internationally, palaeolimnological research has demonstrated that continuously-accreting lake sediment sequences record the sensitivity of many catchments to past and present climate and land use pressures (e.g. Davis 1969; Oldfield et al., 1980; Singh and Geissler, 1985; Renberg, 1990; Zolitschka, 1998; Oldfield et al., 2003; Lamb et al., 2004; Chiverrell 2006). In the temperate context, Coulthard & Macklin (2001) and Foulds & Macklin (2006) suggest that whilst land use change (particularly land use intensification) may lead to greater sediment availability, Holocene upland river systems are driven primarily by climate change. However, they additionally note that anthropogenic land use change renders catchments more sensitive to climate change than would otherwise be the case. Current climate change (especially rainfall) projections (e.g. Hulme et al., 2002) indicate potentially significant consequences for erosion intensity and changes in sediment storage. Upland areas, with high rainfall, thin soils, and frequently intense grazing pressures, are likely to be significantly affected by such changes, with upland lakes also subjected to resultant changes in sediment dynamics and delivery.

The Lake District in the U.K. comprises a spatially dense and interlocking set of upland lake-catchment systems, which can provide a regional perspective on the impact of both climatic and anthropogenic land use change on these sensitive upland systems. Chiverrell (2006) suggests that there have been three key changes in erosion intensity in the history of the Cumbrian lake systems, at ~ 5000 years before present (kyr BP), 2.5 kyr BP and 1 kyr BP. In contrast to Foulds & Macklin's (2006) focus on climate-driven changes in *erosivity*, Chiverrell (2006) links these erosional changes explicitly to anthropogenic land use changes, producing destabilisation of the land surface and increased *erodibility*. In order to disentangle the relative impacts of climate and land use changes on sediment dynamics in this region, it is necessary to examine the sediment record over longer, Holocene timescales, supported by robust chronological control. Present day problems of accelerated lake sediment fluxes also require evaluation over both the historical and pre-historical timescale, in order to assess their relative significance compared with the 'natural' post-glacial evolution of the lake. Here, we examine the sedimentation history and dynamics for Bassenthwaite Lake, designated a Site of Special Scientific Importance but presently subjected to fluxes of phosphorus and fine sediment, associated with eutrophication and loss of spawning habitat for the rare fish, the vendace (Winfield et al, 2004).

The 240km^2 catchment of Bassenthwaite Lake, situated in the north of the Lake District National Park, encompasses three river systems, and the lakes, Derwent Water and Thirlmere (figure 1). Catchment geology is dominated by the Skiddaw Slate Group, with rolling moorland fells in the north and east dominating the River Derwent and Chapel Beck sub-catchments, in contrast with the more mountainous and hydrologically 'flashy' Newlands sub-catchment to the south-west. Much of the catchment exceeds 250 m altitude and is designated 'upland' and 'seriously disadvantaged' (DEFRA, 2008) in terms of its agricultural production, climate, soils and relief. Present day land use is dominated by pastoral farming in the valley bottoms, concentrated in riparian areas. Additionally, several large forest plantations exist both adjacent to and south of the lake. Settlements are tightly clustered between Derwent Water and Bassenthwaite with Keswick (pop. ~ 5,000) the major urban centre within the catchment, which supports a total population of around 7,000 (National Statistics, 2008), rising with summer visitors to 11,000. Historically, land-use has included significant mining of lead, copper and baryte, initiated as late as the early nineteenth century in the previously unexploited Newlands ('new lands') Valley. However, only ~4 % of the present catchment retains any native forest cover, and evidence for human activity from Neolithic times (e.g. Castlerigg stone circle) indicates a long history of land-use change in the Bassenthwaite catchment. Significant increases in lake sediment flux within the last 200 years have been identified from analysis of a 1-metre/~2,000 year record of sedimentation in Bassenthwaite (Hatfield et al., in press). These recent increases have been causally linked with mining activity and deforestation in the late 19th century, and increased winter rainfall in the early 21st century. However, as noted by Chiverrell (2006), other lakes in the region appear to have recorded significant catchment and climate changes from the early Holocene onwards. Here, we examine a longer sediment sequence obtained from Bassenthwaite Lake, to identify rates and sources of sediment flux, and changes in the pollen record from the catchment, through the Holocene. This longer record should enable identification of the relative impacts of climate- and land use-related forcings on sediment dynamics in the Bassenthwaite Lake and catchment.

Methodology

Lake sediment coring and sample preparation

Lake sediment mini-cores obtained previously (Hatfield et al., in press) indicate lowest lake sedimentation rates in the deepest part of the Bassenthwaite basin. Thus, to obtain the longest sediment time series, two 3-meter cores (BASS 8 and 9) were recovered using a Mackereth corer (December 2004), from the deep basin, adjacent to a previous mini-core, BASS 5, a 1-metre core dated using ^{210}Pb methods (Hatfield et al., in press). On return to the laboratory, the cores were opened using a circular saw to cut the plastic liner, producing two undisturbed core halves. One half of each core was sampled into two 1.5 m u-tube channels for palaeomagnetic analyses. The remaining half of BASS8 was sampled continuously at 2 cm intervals, for mineral magnetic analysis of individual sediment samples. These single samples were then split into five particle size fractions, first by wet sieving at 63 μm, and subsequent separation of the 31-63 μm, 8-31 μm, 2-8 μm and <2 μm fractions by settling in Atterberg columns. The magnetic properties of the medium silt-sized fraction (31-63 μm) provide effective means of discrimination between potential catchment sediment sources at the present day (Hatfield & Maher, 2008). Use of this size fraction for sediment sourcing also precludes any confounding influence of possible authigenic, bacterial magnetite phases (Hatfield & Maher, 2008; Hatfield et al., in press). For direct comparability, the majority of magnetic measurements reported here were performed on this size fraction. The sized samples were dried overnight at 40 °C and immobilised in 10 cc plastic pots prior to magnetic analysis.

Palaeomagnetic and mineral magnetic measurements

U-channels taken from the undisturbed half of each sediment core (2 x 1.5 m u-channel lengths per core) were analysed using a pull-through Superconducting QUantum Interference Device (SQUID) magnetometer at the National Oceanography Centre in Southampton. The cores were scanned at 1 cm resolution to measure their natural remanent magnetisation (NRM) intensity, magnetic declination and inclination. Stepwise alternating field (AF) demagnetisation of the NRM was performed, at 5, 10, 15, 20, 25, 30, 40, 50, 60 and 80 milliTesla (mT). The sediments were then subjected to acquisition of an anhysteretic remanence (ARM), in a peak AF of 90 mT with a biasing field of 0.05 mT. In turn, this artificial remanence was stepwise AF demagnetised at 10, 20, 25, 30, 40 and 60 mT. A 'saturation' remanence (SIRM) was then imparted, using a DC field of 900mT, again with subsequent AF demagnetisation (using the same fields as for the ARM demagnetisation process). All measurements are expressed in volumetric units (m A^{-1}). As the cores are unorientated, magnetic declination values were transformed into arbitrary values about 0° (using the methodology of Turner and Thompson, 1981). Data obtained from 5 cm above and below the ends of each u-channel section were removed from the remanence datasets to avoid edge effects in the measurement process and any post-sampling sediment expansion/deformation.

For the single sediment samples, room temperature magnetic measurements included low field, initial magnetic susceptibility (χ_{lf}), susceptibility of anhysteretic remanence (χ_{ARM}, i.e. the ARM normalised by the DC bias field) and stepwise acquisition and demagnetisation of isothermal remanent magnetisation (IRM). Magnetic susceptibility was measured at 0.47 kHz on a Bartington MS2B susceptibility sensor. The ARM was imparted using a Molspin demagnetiser with ARM attachment in a peak ac field of 80 mT, with a superimposed D.C. biasing field of 0.08 mT. IRM acquisition was incrementally imparted in D.C. fields of 20, 40, 50, 100, 200 and 300 mT, using a Molspin pulse magnetiser, and at 500, 700 and 1000 mT (regarded as the saturating field), using a Newport electromagnet. Between the IRM acquisition steps at 100 mT and 700 mT, samples were demagnetised in a tumbling ac field of 100 mT, in order to discriminate between maghemite, haematite and goethite, all of which are capable of high-field IRM acquisition but with differing degrees of magnetic stability (Liu et al., 2002; Maher et al., 2004). The SIRM was stepwise AF demagnetised in fields of 5, 10, 15, 20, 30, 40, 80 and 100 mT. All remanence measurements were made on a Molspin Minispin fluxgate magnetometer (noise level ~ 5×10^{-8} Am^{-1}) and all data are expressed on a mass-normalised basis. From these measurements, several concentration-independent, inter-parametric ratios were also calculated. All magnetic measurements were made at the Centre for Environmental Magnetism and Palaeomagnetism (CEMP) at the Lancaster Environment Centre, Lancaster University. Subsequently, statistical matching of the lake sediment samples against potential source materials (Hatfield and Maher, 2008), on the basis of four independent magnetic parameters, was performed using fuzzy cluster analysis. The fuzzy analysis enables the degree of affinity between a sample and all other clusters to be estimated, rather than the categorical assignment of samples to one cluster, as in conventional hierarchal cluster analysis.

Radiometric dating

Fourteen bulk sediment samples from BASS 8 were ^{14}C-dated, using accelerator mass spectrometry methods, at Lund University, Sweden. Dates were calibrated using atmospheric data from Reimer (2004) and OxCAL v3.10 (Bronk Ramsey, 2005) and a weighted average based on the probability distribution functions of calibrated age ranges was used to obtain best estimates of each date's central point (Telford, 2004). The base of adjacent mini-core BASS 5 (64 cm below lake floor) was also ^{14}C-dated at Lund, at 2,605 calendar years BP.

Pollen Analysis

Standard preparation techniques (acetolysis and hydrofluoric acid treatment) were applied to samples at ~ 10 cm intervals through the BASS 8 sediments, in order to concentrate the constituent pollen grains. A minimum sum of 300 pollen grains was counted for each sample interval (Gilbert, 2008).

Results

Age Control

For robustness, palaeomagnetic dating of sediments using palaeosecular variation (PSV) should be based on at least two records from the same sequence (e.g. Turner and Thompson, 1981; Sagnotti et al., 2005). The palaeomagnetic data from the upper 1.5 m of the two 3-m Bassenthwaite cores, BASS 8 and 9 suggest that a single dominant ferrimagnetic component is responsible for their NRM, all Zjiderveld plots displaying linear demagnetisation trajectories which trend towards the origin. Below ~ 1.5 m depth, magnetic inclination shallows significantly and physical disturbance of the palaeomagnetic directions appears likely to have occurred. Figure 2a shows the correlated magnetic inclination records, af demagnetised at 30mT, for BASS 8 and BASS 9, together with the Windermere master curve (Turner and Thompson, 1981), supported by the 14 ^{14}C dates as independent tie-points. The palaeomagnetic correlation between BASS 8 and 9 is supported by the down-core variations in SIRM and ARM (figures 2b and 2c). Relative 'lock-in' depths of the palaeomagnetic signal (Sagnotti et al., 2005) vary only slightly between the cores (ranging from -5 to 4 cm) resulting from slightly differing sedimentation rates. These two sediment cores thus appear to provide a representative record of sedimentation in the deep basin of Bassenthwaite Lake. Hatfield et al. (in press) recovered several 1-m cores from Bassenthwaite, all of which display distinctively high values of SIRM and susceptibility at between ~ 15 and 45 cm depth (^{210}Pb-dated to ~ 1960). These distinctive magnetic peaks are absent from BASS 8 and 9, suggesting that the most recent sediments are missing from both 3-m cores. The top of BASS 8 correlates with the base of mini-core BASS 5 on the basis of 2 ^{14}C dates and the distinctive dominant presence of the diatom taxa, *Cyclotella comensis* and *Cyclotella bodanica.* To obtain the most complete and continuous sediment record for the lake so far, BASS 5, the longest of the 1-m mini-core records, can thus be superimposed on the 3-m BASS 8 core (figures 3a and 3b). BASS 8 was selected due to its slightly higher sedimentation rate and better resolved PSV, SIRM and ARM records. The BASS 8 PSV record deteriorates at > 1.36 m depth; below this, the ^{14}C dates also show greater spread and possibly indicate incorporation of/contamination by younger carbon at depth (figure 3c). Given that errors from the ^{14}C reservoir effect potentially exceed those from the PSV-based record, the age model for the lower part of BASS 8 is derived from extrapolation of the relatively constant linear sedimentation rate occurring between 0.8 and 1.36 m in the PSV record (figure 3c). This PSV-based model bisects the scattered radiocarbon dates at the base of the core. Comparison of these fitted BASS 8 age/depth profiles with the adjacent BASS 5 mini-core record indicates they have comparable accumulation rates (0.05 cm yr^{-1}) prior to the last ~ 500 years (figure 3d). By integrating the higher resolution mini-core record of recent sedimentation and the multi-millennial long core record, we can thus examine sediment dynamics over the last ~ 5,500 years of Bassenthwaite Lake's existence.

Sediment Physical Properties

Figure 4 shows the percentage change of the clay and coarse silt fractions with sediment depth in the integrated BASS 8/BASS 5 core record. From ~ 5.5 kyr BP to 4.8 kyr BP, the sediment particle size distribution is relatively fine and varies little. From ~ 4.8 kyr BP, particle size becomes more variable and from 4.2 kyr BP distinct fining occurs, illustrated by a ~15 % increase in the proportion of clay. Around 3.8 kyr BP, particle size becomes less variable, with a relatively fine size distribution maintained for ~1 kyr before progressive coarsening of the sediment ensues. At ~ 2.1 kyr BP (i.e. the correlation point between the BASS 5 mini-core and the BASS 8 3 m core), particle size variations in both cores are small and comparable. Subsequent coarsening of the lake sediment occurs, with a peak at ~ 1.5 kyr BP, with increases of 5 % and 10 % in the coarse and medium silt fractions, respectively. Significant particle size changes occur again during the last 50 years. Figure 3d shows the sediment accumulation rate based on the integrated ^{210}Pb- and PSV-based age/depth reconstruction shown in figure 3c. Increases in sediment flux (up to 0.2 cm yr-1) are recorded at ~ 4 kyr BP, 3.4 kyr BP and 2.5 kyr BP. However, these are small in magnitude compared with the highest sediment flux values (up to 0.6 cm yr^{-1}) which occur in three distinct 'pulses' within the last ~ 150 years (Hatfield et al., in press; Bennion et al., 2000).

Magnetic Properties

The majority of the Bassenthwaite Lake sediments are dominated magnetically by ferrimagnetic minerals (magnetite and maghemite), as shown by characteristically steep IRM acquisition curves, with 82 % (±2% as 1 std dev.) of the SIRM attained at 100 mT. However, higher coercivity magnetic components are also present, as indicated by ~ 18 % remanence acquisition in applied fields > 300 mT. Some of this higher field remanence may be attributable to maghemite which, although ferrimagnetic, can acquire remanence at such fields (but this remanence is completely unstable when subjected to af demagnetisation, Liu et al., 2002; Maher et al., 2004). Some 68 % ($\underline{+}$ 8% as 1 s.d.) of the $HIRM_{1\text{-}0.1\ T}$ is lost upon 100mT a.f. demagnetisation. The remaining, stable high-field remanence reflects the presence of goethite or haematite. Based on the stable HIRM component, the haematite content of the sediments is ~ 0.043 %, with a ferrimagnetic concentration (probably magnetite) of ~ 0.016 % estimated from the soft remanence (IRM_{100mT}). Although there is almost 3 x the concentration of haematite to magnetite in the samples, the sediment magnetic properties are dominated by the ferrimagnetic contributions.

Figure 5 shows the integrated down-core profile of concentration-dependant and ratio magnetic parameters for the Bassenthwaite Lake record. The concentration-dependant parameters, χ_{lf} and SIRM, show similar variations, with low and declining values from the basal sediments up to ~ 2 kyr BP, when values stabilise. Only from the 19th century onwards do sharp maxima in χ_{lf} and SIRM occur. The χ_{ARM} behaviour differs from that of χ_{lf} and SIRM. Maximum χ_{ARM} values are recorded between 5 kyr BP and 3.5 kyr BP, falling to minimum values around 2.5 kyr BP. Relatively low χ_{ARM} values then persist before increases towards the core top, in similar fashion to χ_{lf} and SIRM. The inter-parametric ratios (e.g. IRM_{100mT}/SIRM, χ_{ARM}/χ_{lf}, χ_{ARM}/SIRM, MDF_{IRM} and $SIRM_{-100mT}$ a.f. (%)) are independent of magnetic concentration. They reflect changes in the mineralogy and grain size of the sediment magnetic minerals. Two major periods of change are shown by these parameters. First, from 5 – 3.5 kyr BP, χ_{ARM}/χ_{lf} and χ_{ARM}/SIRM reach maximum values and MDF_{IRM} increases, suggesting the presence of finer and harder magnetic minerals. Second, within the last 500 years, values of χ_{ARM}/χ_{lf} and χ_{ARM}/SIRM decrease, presaging the major changes in all magnetic parameters at ~ 150 years BP (Hatfield et al., in press).

At the present day, suspended sediments transported to Bassenthwaite Lake by the Derwent and Newlands Beck can be differentiated on the basis of their magnetic and elemental properties (Hatfield & Maher, 2008). If it is assumed that these inflows and sources have also been operative in the past, then their relative contribution to the 5.5 kyr-long lake sediment record can be estimated, from statistical matching of the sediments with these sources. Fuzzy cluster analysis returns no ‘unclassified’ samples (suggesting the absence of any ‘non-analogue’ sources in the record). The Derwent is identified as the dominant source of the lake sediment from 4.5 kyr to 0.5 kyr BP (figure 6), in association with relatively low values of sediment flux (estimated from X_{lf}, e.g. Thompson and Oldfield, 1986; Dearing 1999, Hatfield et al., in press). In contrast, Newlands Beck is the major sediment source from 5.6 kyr to 4.5 kyr, and again from 300 yr to present, and appears to be associated with the highest sediment fluxes recorded from the mid-Holocene onwards.

Pollen Record

Percentage pollen counts representing the major vegetation classes are presented in figure 7. Based on the arboreal/non-arboreal pollen ratio and % changes in some indicator species, six local pollen zones (LPZ) can be defined for the Bassenthwaite sediment record. LPZ1 (5.6 – 4.8 kyr BP) is dominated by deciduous trees, with total arboreal pollen (AP) ~ 70-80 % and *Quercus* (oak), *Alnus* (alder), *Corylus* (hazel) and *Betula* (beech) the most common species. LPZ2 (4.8 – 4.0 kyr BP) shows declines in oak and beech, accompanied by increases in alder, *Poaceae* (grasses) and *Pteropsida* (ferns). LPZ3 (4.0 – 2.5 kyr BP) is characterised by a further decline in AP (particularly oak) and establishment of more permanent grassland in the catchment. LPZ4 (2.5 kyr – 1.5 kyr BP) shows increases in grasses and herbs, particularly *Plantago lanceolota* and *P. spathulata* and an increase in *Erica* (heather). LPZ6 (300 BP – present) is characterised by large increases in herbs and grasses, further declines in oak and beech, and increases in *Pinus* (pine) and *Alnus* (alder)

Archaeological Finds

Evidence for evolving human occupation and land use change in the Bassenthwaite catchment during the mid- to late-Holocene is provided by records of archaeological finds (figure 8). Whilst it should be noted that absence of finds does not necessarily indicate absence of activity, these data can be used to map human activity and occupation in certain periods (as defined by the Archaeological Data Service). For the Bassenthwaite catchment, the earliest evidence (prehistoric, Mesolithic and Neolithic) is concentrated in the flat valley bottoms around what is now Keswick and St John’s in the Vale, and adjacent to the three lakes (figure 8a). Evidence for later finds, from the Bronze and Iron Ages (figure 8b), show greater spread, with first evidence for activity both at higher altitudes and more distal locations. The Romans greatly developed the Greta and Glenderamackin valleys (figure 8c), following the earlier concentrated activity within these areas. Notably, there are few pre-medieval finds in the Newlands valley; much of the development here is confined to much later, medieval and post-medieval periods.

Discussion

Changes in the rate of sediment flux, sediment physical and magnetic properties and in pollen assemblages through the sedimentary record of Bassenthwaite

Lake reflect changes in climatic and/or land-use forcing mechanisms. The observed changes in sediment particle size (figure 4), for example, could arise from changes in energy in the system (see synchronicity evident in figures 4 and 6c), and/or in supply of sediment either from the catchment or from within-lake redistribution processes. Here, the multiproxy sediment data can be used to evaluate the respective roles of climate and human activity in changing the sediment dynamics of the lake over the last ~ 5.5 kyrs.

LPZ 1, ~ 5.6 – 4.8 kyr BP: The pollen record indicates dominant mixed deciduous woodland cover in the lake catchment, with alder carr probably prevalent on the poorly-drained valley floors and lower floodplains, oak more dominant on the better drained foothills and shallow slopes. Fluctuating AP percentages (between 60 and 80 %), together with low concentrations of herbaceous species (*Plantago, Rumex* and *Filipendula*) indicate early if restricted human activity, supported by prehistoric and Meso- and Neolithic archaeological evidence (e.g. construction of Castlerigg stone circle date at ~5 kyr BP). From the magnetic data, rates of sediment flux to the lake are low. Around 5.0 – 4.8 kyr BP, in association with relatively warm and wet climate conditions (fig. 6b and c), slight increases in SIRM and χ_{LF} occur, associated with the Newlands valley source, and the particle size of the lake sediments coarsens slightly. Inwash of 'old' carbon, indicated by reversals in the ^{14}C dates, may also have occurred. Although it is clear that the Newlands valley did not undergo significant development until relatively very late, its steep terrain is likely to have been more susceptible to flashy storm run-off, and efficient sediment delivery compared with the more undulating Derwent sub-catchment. Thus, slightly enhanced storm activity may be responsible for these minor changes in lake sediment source and flux at a time when human catchment disturbance and sediment flux were generally low.

LPZ2, ~ 4.8 – 4.0 kyr BP: For this time interval, the lake edges, floodplains, flat valley floors and lower slopes are where the majority of early archaeological finds have been found (figure 8a). Decreases in AP percentages (particularly oak) between 4.8 and 4.2 kyr BP reflect increased human activity and forest clearance, with the archaeology indicating most activity within the more accessible Derwent sub-catchment. Climatic and vegetation conditions in the mid-Holocene were likely to have been favourable for magnetic enhancement in cambisols (Maher, 1998; Maher et al., 2003); increased topsoil erosion linked to deforestation episodes may explain increased fining of the lake's magnetic minerals at this time, and evident in the coarse silt fraction possibly due to incomplete particle size separation (e.g. Sartori et al., 2005). The magnetic properties of the lake sediments display statistical affinity with the Derwent rather than Newlands Beck at this time (figure 6a) reflecting the uneven concentration of human activity. Towards the end of LPZ2 (~4.0 kyr BP), forest regeneration is evident,, as humans dispersed away from the lake edges and along the Greta and St. John's valleys. Rates of sediment flux at this time are low, indicating little impact of the climatic decline (from ~ 5 to ~ 2 kyr BP) following the mid-Holocene 'optimum', associated with a fall in annual average temperature and increased rainfall, as shown by a number of UK records (e.g. figures 6b and 6c; Chambers et al., 1997; Langdon and Barber, 2005; Dalton et al., 2005; Langdon et al., 2004; Coulthard and Macklin, 2001).

LPZ3, ~ 4.0 – 2.8 kyr BP: Bronze Age settlements around Threlkeld and more substantial earthworks in St. John's in the Vale indicate increasing human occupation concentrated along the Greta and Glenderamackin river valleys (ADS, 2008), associated with pollen evidence of increased deforestation and more sustained establishment of semi-permanent grassland. Sediment flux increased, with contributions from the Derwent peaking at ~ 3.8 kyr BP. From this time, significant changes occur in lake sediment properties, with decreases in all magnetic concentration parameters and clastic coarsening. This may reflect increases in subsoil (rather than topsoil) erosion and/or increased frequency of sediment suspension events, possibly including increased sediment redistribution from the shallow to the deeper areas of the lake (Hatfield et al., in press). Despite evidence for increased catchment disturbance, sediment flux rates to the deep basin remain low, suggesting storage of sediment storage elsewhere (floodplains, shallow lake areas).

At the present day, the Derwent floodplain and aggrading delta are large sediment stores, and much of Bassenthwaite, especially close to the Derwent inflow, is < 5 m in depth (in contrast to the deep westerly basin, > 20 m depth). Increased local deposition may have reduced the apparent flux of Derwent-sourced sediment to the deeper basin. In contrast with LPZ1, there is little evidence of Newlands-sourced sediments in the deep basin at this time.

LPZ4,, 2.8 – 1.5 kyr BP: Increases in the catchment's population and settled agriculture are indicated by the archaeological finds from the late Iron Age and Romano-British period and increasing pollen percentages of *Plantago* and *Rumex*, especially from ~ 2.5 kyr BP. Evidence exists for Roman roads along the Glenderamackin river valley and around Braithwaite, with extensive fort and settlement developments around Troutbeck, Threlkeld and Keswick (ADS, 2008). A second major decline in oak pollen indicates renewed and substantial deforestation, possibly on the shallower slopes of the Newlands valley. Increased archaeological finds (ADS, 2008) and an interval of increased lake sediment flux from the Newlands valley appears to support this. However, rates of sediment flux decrease almost immediately and the Derwent is reinstalled as the major lake sediment source. Roman occupation significantly impacted vegetation and/or erosional flux in many Lake District catchments (Oldfield, 1963; Wimble et al., 2000; Chiverrell, 2006). Bassenthwaite shows relatively little response despite evidence of significant catchment disturbance concentrated in the Greta and Glenderamackin river valleys. This again suggests significant sediment storage, especially within the Derwent sub-catchment.

LPZ 5, ~ 1.5 – 0.3 kyr BP: Most of the archaeological finds in the Newlands sub-catchment date from medieval and post-medieval times (ADS, 2008). Despite onset of these late changes in the Newlands valley, the Derwent remained the main sediment source through most of this time interval. More intense post-medieval activity was initiated through mining, first of copper and then, much later, of lead (Postlethwaite, 1913). Increased pollen percentages of *Erica* indicate higher proportions of moorland development, coupled with conversion of heath at lower altitudes to pasture for sheep grazing, particularly in riparian areas. Sediment fluxes show little increase at this time, however.

LPZ 6, ~ 300 years BP – Present: Increasing land use pressures, particularly in the Newlands valley, appear associated with major changes in the sediment regime within this time period. Doubling of herb and grass pollen percentages and a further 10 % reduction in AP indicate increased deforestation, large-scale establishment of pasture, and increasingly intensive pastoralism as the dominant land use in the upland areas. When upland vegetation cover is converted from relatively deep-rooted woodland and ferns to shallow-rooted pasture, markedly increased rates of soil erosion result (Wilmshurst, 1997; Wilmshurst & McGlone 2005). A first 'pulse' of increased lake sediment flux at Bassenthwaite is evident at ~ 500 yrs BP, and a second at ~ 300 yrs BP. However, the most dramatic increases (> x 3) in sediment flux occur at ~ 150 yrs BP, dominated by Newlands-sourced material. In addition to these intensified agricultural activities, mining and deforestation in the Newlands valley in the 18th and 19th centuries appear to have resulted in major erosional activity and sediment delivery to the lake. Not only is sediment supply likely to have been increased but also sediment delivery, since artificial straightening and river bank revetment along the Newlands Beck was undertaken during and post – World War 2. Another major 'pulse' of sediment flux coincides with renewed farming intensification during the 1960s. Most recently (and ongoing), a further interval of increased sediment flux, again Newlands-sourced, has been initiated within the last ~ 10 years.

Implications for upland catchments

Evidence from these multiproxy records indicates a stepwise increase in human impacts on sediment dynamics in the Bassenthwaite catchment only within the last 150 years, despite pollen and archaeological evidence for human activity and occupation through the last ~ 5.5 kyrs. Either this activity was insufficient to alter catchment sediment dynamics and/or sediment storage and redistribution has until recently ‘buffered’ sediment influx to the deep lake basin. Any such buffers appear to have been exceeded by recent, intense land use and river channel changes in the Newlands catchment. The combination of increased sediment supply and decreased sediment storage (on floodplains and in channels) has resulted in rapid and ongoing acceleration of sediment influx to the lake. Given predictions and observations of increased rainfall and storm intensity linked to global warming (Hulme et al., 2002; Malby et al., 2007), the ecological status of Lake Bassenthwaite, already progressing towards eutrophy (Bennion et al., 2000), is likely to deteriorate further and rapidly, unless accelerated sediment supply is mitigated (e.g. by land use change, such as reafforestation) and sediment storage capacity restored (e.g. by restoration of river channels).

Conclusions

- From the mid-Holocene onwards, sedimentation rates at Lake Bassenthwaite have been low (~ 0.05 cm/yr), despite increased rainfall and slightly declining temperatures. Catchment disturbance by human activity has been relatively limited and late. Newlands Beck-sourced sediment dominated the early part (5.5 – 4.5 kyr BP) of the deep lake basin record. Sediment source then shifted to the River Derwent, with sediment accumulation rates of ~ 0.05 - 0.1 cm/yr from ~ 4.5 kyr BP, until the last ~ 500 years when Newlands sources became dominant, in association with major (> 3 x) increases in sedimentation rate.
- Pollen analysis, allied with published archaeological finds data, indicates increasing human activity and environmental impact from the mid-Holocene onwards but increases in rates of sedimentation only occur in recent times, particularly reflecting the late and intense land use changes in the Newlands Beck subcatchment.
- Sediment storage processes are important in the Bassenthwaite catchment, with Derwent-sourced sediment probably preferentially deposited in the shallower areas of the lake, especially at the aggrading pro-Derwent delta.
- Increased land-use intensification in the Newlands Valley over the last ~ 500 years, coupled with increasing channalisation of Newlands Beck, has

increased sedimentation rates and reduced sediment storage on the floodplain.

- Factors controlling lake sediment distribution, supply and floodplain storage each contribute to the Bassenthwaite lake sediment record, with the deep lake basin most sensitive to changes in sediment flux from the Newlands valley.

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References

Appleby, P.G. and Oldfield, F. 1978. The calculation of lead-210 dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. *Catena,* 5, 1-8

ADS (2008) Archaeology Data Service, Arc search catalogue, University of York. http://ads.ahds.ac.uk/catalogue/ Retrieved 04-04-2008

Bennion, H., Monteith, D., Appleby, P. 2000. Temporal and geographical variation in lake trophic status in the English Lake District: evidence from (sub)fossil diatoms and aquatic macrophytes. *Freshwater Biology*, 45, 394-412.

Birks, H.J.B. 1986. Numerical zonation, comparison and correlation of Quaternary pollen-stratigraphical data. In Berglund, B.E. (editor) *Handbook of Holocene Palaeoecology and Palaeohydrology.* The Blackburn Press

Bradshaw, R. & Thompson, R. 1985. The use of magnetic measurements to investigate the mineralogy of Icelandic lake-sediments and to study catchment processes. *Boreas*, 14, 203-215.

Bronk Ramsey, C. 2005: Improving the resolution of radiocarbon dating by statistical analysis. In Levy, T. E. & Higham, T. F. G. (editors) *The bible and radiocarbon dating: archaeology, text and science*. Equinox.

Chambers, F.M., Barber, K.E., Maddy, D. and Brew, J. 1997. A 5500-year proxy-climate and vegetation record from blanket mire at Talla Moss, Borders, Scotland. *The Holocene*, 7, 391-399

Chiverrell, R.C. 2006. Past and future perspectives upon landscape instability in Cumbria, northwest England. *Regional Environmental Change*, 6, 101-114.

Collins, A. L. and Walling, D. E. 2002. Selecting fingerprint properties for discriminating potential suspended sediment sources in river basins. *Journal of Hydrolog*y, 261, 218-244.

Coulthard, T. J. and Macklin, M.G. 2001. How sensitive are river systems to climate and land-use changes? A model-based evaluation. *Journal of Quaternary Science*, 16, 347-351.

Dalton, C., Birks, H.J.B., Brooks, S.J., Cameron, N.G., Evershed, R.P., Peglar, S.M., Scott, J.A. and Thompson, R. 2005. A multi-proxy study of lake-development in response to catchment changes during the Holocene at Lochnagar, north-east Scotland. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 221, 175-201

Davis, M.B. 1969. Climatic changes in Southern Connecticut recorded by pollen deposition at Rogers Lake. *Ecology*, 50, 409-422.

Dearing, J. 1999: Holocene environmental change from magnetic proxies in lake sediments. In Maher, B.A. and Thompson, R. (editors) *Quaternary Climates, Environments and Magnetism*. Cambridge University Press, 231-278

DEFRA (2008) Uplands land classification. http://www.defra.gov.uk/rural/uplands/land-classification.htm Retrieved 04-04-2008

Foster, I.D.L. and Walling, D.E. 1994. Using reservoir deposits to reconstruct changing sediment yields and sources in the catchment of the Old Mill Reservoir, South Devon, UK, over the past 50 years. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques*, 39, 347-368.

Foulds, S. A. and Macklin, M.G. 2006. Holocene land-use change and its impact on river basin dynamics in Great Britain and Ireland. *Progress in Physical Geography*, 30, 589-604.

Gilbert, C. 2008. Has Northern-Lake District vegetation changed during the late Holocene as a result of anthropogenic or climate forcing. Unpublished uundergraduate dissertation, Department of Geography, Lancaster University

Hatfield, R.G. and Maher, B.A. 2008. Suspended sediment characterisation and tracing using a magnetic fingerprinting technique: Bassenthwaite Lake, Cumbria, UK. *The Holocene*, 18, 105-115

Hatfield, R.G., Maher. B.A., Pates, J.M. and Barker, P.A. in press. Sediment dynamics in an upland temperate catchment: changing sediment sources, rates and deposition. *Journal of Paleolimnology*, in press

Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., Mcdonald, R. and Hill, S. 2002: Climate change scenarios for the United Kingdom: The UKCIP02 Scientific Report, Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia.

Kodama, K. P., Lyons, J. C., Siver, P. A. and Lott, A. M. 1997. A mineral magnetic and scaled-chrysophyte paleolimnological study of two northeastern Pennsylvania lakes: Records of fly ash deposition, land-use change, and paleorainfall variation. *Journal of Paleolimnology*, 17, 173-189.

Lamb, A.L., Leng M.J., Mohammed, M.U. and Lamb, H.F. 2004. Holocene climate and vegetation change in the Main Ethiopian Rift Valley, inferred from the composition (C/N and $\delta^{13}C$) of lacustrine organic matter. *Quaternary Science Reviews*, 23, 881-891

Langdon, P.G. and Barber, K.E. 2005. The climate of Scotland over the last 5000 years inferred from multiproxy peatland records: inter-site correlations and regional variability. *Journal of Quaternary Science*, 20, 549-566

Langdon, P.G., Barber, K.E. and Lomas-Clarke, S.H. 2004. Reconstructing climate and environmental change in northern England through chironomid and pollen analyses: evidence from Talkin Tarn, Cumbria. *Journal of Paleolimnology*, 32, 197-213

Libby, W. F. 1955: Radiocarbon dating, University of Chicago Press.

Liu, Q. S., Banerjee, S. K., Jackson, M. J., Zhu, R. X. and Pan, Y. X. 2002. A new method in mineral magnetism for the separation of weak antiferromagnetic signal from a strong ferrimagnetic background. *Geophysical Research Letters*, 29, (6) 1-4

Locke, G. and Bertine, K.K. 1986. Magnetite in sediments as an indicator of coal combustion. *Applied Geochemistry*, 1, 345-356

Maher, B.A. 1998. Magnetic properties of modern soils and loessic paleosols: implications for paleoclimate. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 137, 25-54.

Maher, B.A. Alekseev, A.O. and Alekseeva, T. 2003. Magnetic mineralogy of soils across the Russian steppe: climatic dependence of pedogenic magnetite formation. *Paleogeography, Plaeoclimatology, Palaeoecology*, 201, 321-341.

Maher, B. A., Karloukovski, V. V. and Mutch, T. J. 2004. High-field remanence properties of synthetic and natural submicrometre haematites and goethites: significance for environmental contexts. *Earth and Planetary Science Letters*, 226, 491-505.

Malby, A.R., Whyatt, J.D., Timmis, R.J., Wilby, R.L. and Orr, H.G. 2007. Long-term variations in orographic rainfall: analysis and implications for upland catchments. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* 52, 276-291

National Statistics (2008) Neighbourhood Statistics http://www.neighbourhood.statistics.gov.uk/dissemination/ Retrieved 04-04-2008

Nelson, D. E., Korteling, R. G. and Stott, W. R. 1977. Carbon-14 direct detection at natural concentrations. *Science*, 198, 507-508.

Oldfield, F. 1963. Pollen analysis and man’s role in the ecological history of the south-east Lake District. *Geografiska Annaler* 45, 23-40

Oldfield, F. and Appleby, P. G. 1984. A combined radiometric and mineral magnetic approach to recent geochronology in lakes affected by catchment disturbance and sediment redistribution. *Chemical Geology*, 44, 67-83.

Oldfield, F., Appleby, P.G. and Thompson, R. 1980. Palaeoecological studies of lakes in the highlands of Papua New Guinea. I The chronology of sedimentation. *Journal of Ecology*, 68, 457-477

Oldfield, F., Crooks, P. R. J., Harkness, D. D. and Petterson, G. 1997. AMS radiocarbon dating of organic fractions from varved lake sediments: an empirical test of reliability. *Journal of Paleolimnology*, 18, 87-91.

Oldfield, F., Maher, B. A., Donoghue, J. and Pierce, J. 1985. Particle-size related, mineral magnetic source sediment linkages in the Rhode River catchment, Maryland, USA. *Journal of the Geological Society*, 142, 1035-1046.

Oldfield, F., Wake, R., Boyle, J., Jones, R., Nolan, S., Gibbs, Z., Appleby, P., Fisher, E. and Wolff, G. 2003. The late-Holocene history of Gormire Lake (NE England) and its catchment: a multiproxy reconstruction of past human impact. *Holocene*, 13, 677-690.

Pearsall, W.H. and Pennington, W. 1947. Ecological history of the English Lake District. *Journal of Ecology*, 34, 137-148

Postlethwaite, J. 1913: Mines and mining in the (English) Lake District, Moss.

Reimer P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Herring, C., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Bronk Ramsey, C., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., Van Der Plicht, J., and Weyhenmeyer, C. 2004. IntCal04 terrestrial radiocarbon age calibration, 26 – 0 ka BP. *Radiocarbon*, 46, 1029 - 1058.

Renberg, I. 1990. A 12600 Year Perspective of the Acidification of Lilla-Oresjon, Southwest Sweden. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences*, 327, 357-361.

Rose, N.L. and Appleby, P.G. 2005. Regional Applications of Lake Sediment Dating by Spheroidal Carbonaceous Particle Analysis I: United Kingdom. *Journal of Paleolimnology*, 34, 349-361

Sagnotti, L., Budillon, F., Dinares-Turell, J., Lorio, M. and Macri, P. 2005. Evidence for a variable paleomagnetic lock-in depth in the Holocene sequence from the Salerno Gulf (Italy): Implications for "high-resolution" paleomagnetic dating. *Geochemistry Geophysics Geosystems*, 6, Q11013

Sartori, M., Evans, M.E., Heller, F., Tsatskin, A. and Han, J.M. 2005. The last glacial/interglacial cycle at two sites in the Chinese Loess Plateau: Mineral magnetic, grain-size and ^{10}Be measurements and estimates of palaeoprecipitation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 222, 145-160

Singh, G. and Geissler, E.A. 1985. Late Cainozoic history of vegetation, fire, lake levels and climate at Lake George, New South Wales, Australia. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, 311, 379-447

Telford, R. J., Heegaard, E. and Birks, H. J. B. 2004. All age-depth models are wrong: but how badly? *Quaternary Science Reviews*, 23, 1-5.

Thompson, R., Oldfield, F. 1986: *Environmental Magnetism*, Allen & Unwin.

Turner, G. M. and Thompson, R. 1981. Lake sediment record of the geomagnetic secular variation in Britain during Holocene times. *Geophysical Journal of the Royal Astronomical Society*, 65, 703-725.

von Post, L . 1946. The prospect for pollen-analysis in the study of the earth's climatic history. *New Phytologist* 45, 193-217

Walden, J., Slattery, M. C. and Burt, T. P. 1997. Use of mineral magnetic measurements to fingerprint suspended sediment sources: approaches and techniques for data analysis. *Journal of Hydrology*, 202, 353-372.

Walling, D. E., Peart, M. R., Oldfield, F. and Thompson, R. 1979. Suspended sediment sources identified by magnetic measurements. *Nature*, 281, 110-113.

Wilmshurst, J. M. 1997. The impact of human settlement on vegetation and soil stability in Hawke's Bay, New Zealand. *New Zealand Journal of Botany*, 35, 97-111.

Wilmshurst, J. M. and Mcglone, M. S. 2005. Corroded pollen and spores as indicators of changing lake sediment sources and catchment disturbance. *Journal of Paleolimnology*, 34, 503-517.

Wimble, G., Wells, C. E. and Hodgkinson, D. 2000. Human impact on mid- and late Holocene vegetation in south Cumbria, UK. *Vegetation History and Archaeobotany*, 9, 17-30.

Winfield, I.J., Fletcher, J.M. and James, B. 2004. Conservation ecology of the Vendace (coregonus albula) in Bassenthwaite Lake and Derwent Water, U.K. *Annales Zoologici Fennici,* 41, 155-164

Zolitschka, B. 1998. A 14,000 year sediment yield record from western Germany based on annually laminated lake sediments. *Geomorphology*, 22, 1-17

Figure Captions:

Figure 1: Map of the Bassenthwaite catchment with major inflows, land over 250m in altitude and major mine locations

Figure 2: Correlated whole-core scans of the upper undisturbed 1.5m u-channel of BASS8 and BASS9, showing magnetic (a) inclination relative to the Windermere master curve of Turner and Thompson (1981); (b) SIRM and (c) ARM

Figure 3: Sediment dating and correlation methods for BASS 8: (a) Magnetic susceptibility curve of BASS 5 with ^{210}Pb and ^{14}C dated depths and dates with associated errors; (b) Magnetic susceptibility curve of BASS 8 with ^{14}C dated depths and dates with associated errors (the uppermost susceptibility peak is an artefact, from contamination from the rock saw); (c) integrated age/depth model of BASS 5 and BASS 8 showing BASS5 ^{210}Pb dates (from Hatfield et al., in press), and the PSV and ^{14}C record (with error bars) of BASS8. The dashed lines

show data interpolation (as described in the text); and (d) the integrated magnetic susceptibility record (black line), as a proxy for sediment accumulation rate,, and sediment accumulation rate (cm yr^{-1}, grey line) for BASS 5 and BASS8.

Figure 4: Particle size distribution of the integrated records of BASS5 and BASS8.

Figure 5: Concentration-dependant and concentration-independent magnetic parameters for the integrated records of BASS5 and BASS8.

Figure 6: (a) Magnetic susceptibility as a measure of terrestrial inorganic sediment flux, with the dominant source of sediment identified from the fuzzy clustering solution. Black lines represent a dominant Newlands source and grey lines a dominant Newlands source, respectively; (b) Chironomid-inferred temperature reconstruction from Talkin Tarn, Cumbria (Langdon et al., 2004); and (c) Rainfall proxy, taken from peat humification values from Talla Moss, Southern Scotland (Chambers et al., 1997)

Figure 7: Percentage pollen diagram for selected taxa in BASS5 and BASS8 (bars). Also shown are the percentage groupings of arboreal pollen, herbs and grasses, and ferns and bracken (black fill).

Figure 8: Pre-medieval archaeological finds in the Bassenthwaite catchment according to the Archaeological data service (ADS) plotted in four time bands: (a) Pre ~4 kyr BP; (b) 4 – 2 kyr BP; (c) 2 - 1 kyr BP and (d) all data.

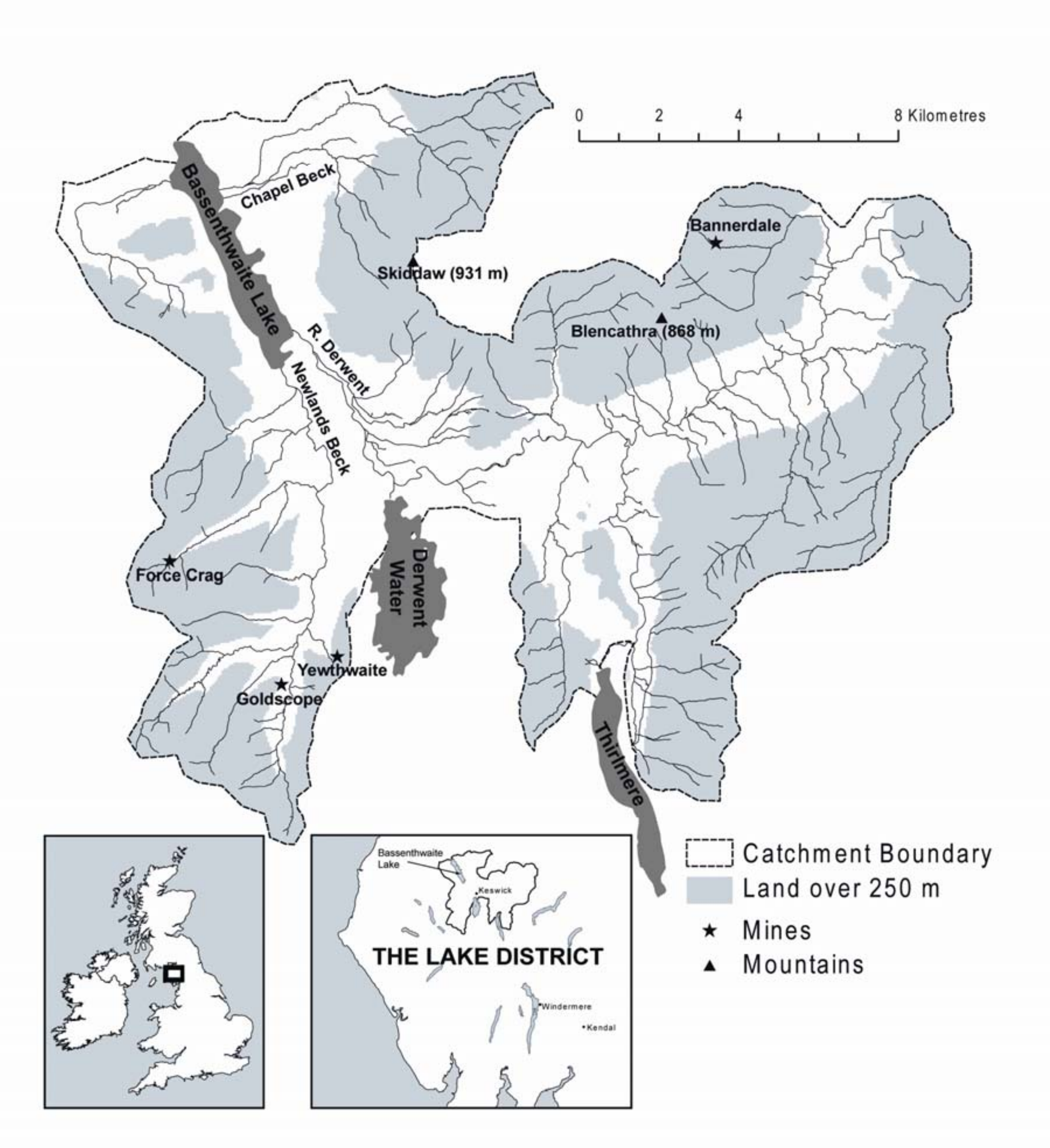

0
2
4
8 Kilometres
Bassenthwaite Lake
Chapel Beck
Skiddaw (931 m)
Bannerdale
Blencathra (868 m)
R. Derwent
Newlands Beck
Derwent Water
Force Crag
Yewthwaite
Goldscope
Thirlmere
Catchment Boundary
Land over 250 m
Mines
Mountains
Bassenthwaite Lake
Keswick
THE LAKE DISTRICT
Windermere
Kendal

Figure 1

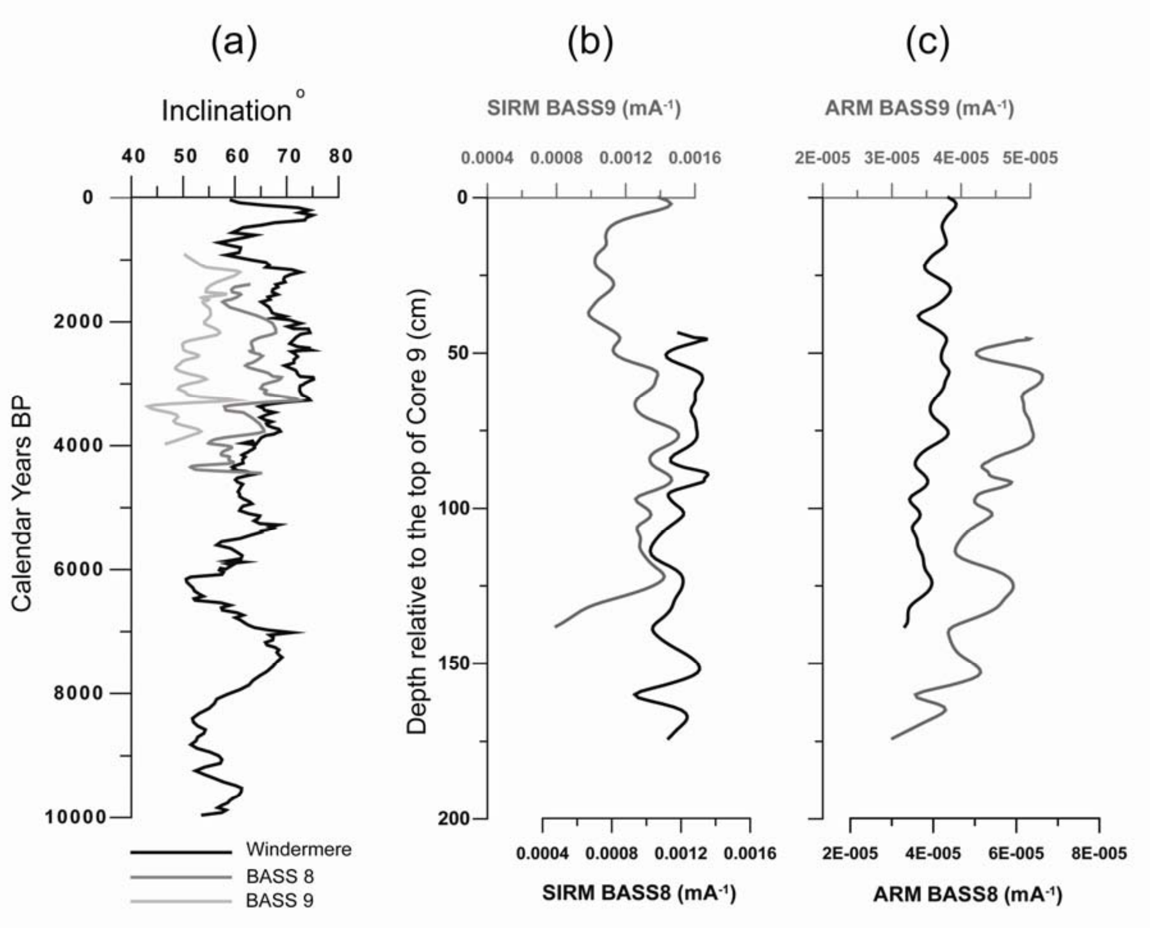

(a)
(b)
(c)
Inclination °
40 50 60 70 80
Calendar Years BP
0
2000
4000
6000
8000
10000
Windermere
BASS 8
BASS 9
SIRM BASS9 (mA-1)
0.0004 0.0008 0.0012 0.0016
Depth relative to the top of Core 9 (cm)
0
50
100
150
200
0.0004 0.0008 0.0012 0.0016
SIRM BASS8 (mA-1)
ARM BASS9 (mA-1)
2E-005 3E-005 4E-005 5E-005
2E-005 4E-005 6E-005 8E-005
ARM BASS8 (mA-1)

Figure 2

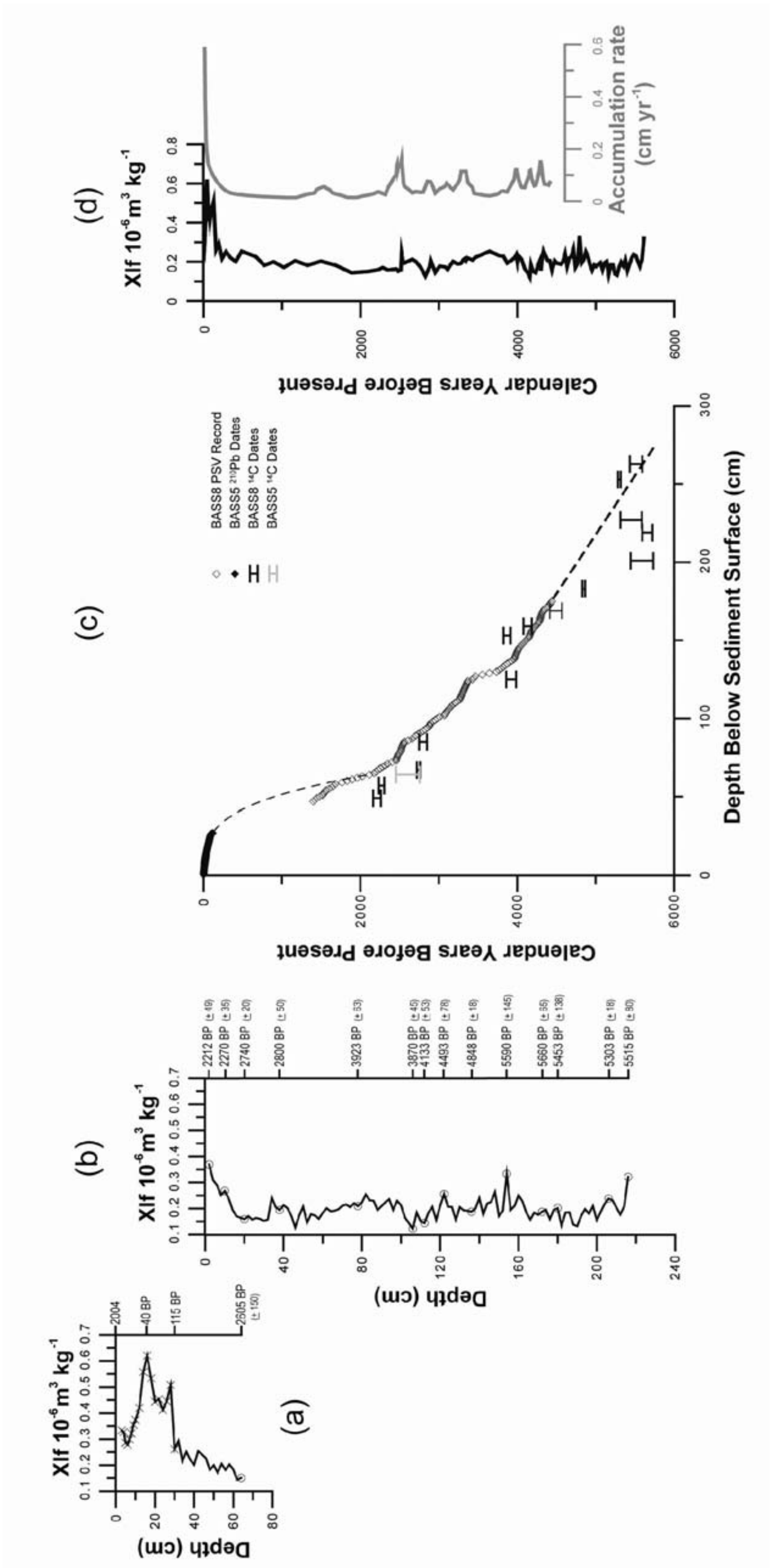

(a)
Xlf 10^{-6}m^3 kg^{-1}
Depth (cm)
2004
40 BP
115 BP
2605 BP (± 150)
(b)
Xlf 10^{-6}m^3 kg^{-1}
Depth (cm)
2212 BP (± 19)
2270 BP (± 35)
2740 BP (± 20)
2800 BP (± 50)
3923 BP (± 63)
3870 BP (± 45)
4133 BP (± 53)
4493 BP (± 78)
4848 BP (± 18)
5590 BP (± 145)
5660 BP (± 65)
5453 BP (± 138)
5303 BP (± 18)
5515 BP (± 90)
(c)
BASS8 PSV Record
BASS5 ^{210}Pb Dates
BASS8 ^{14}C Dates
BASS5 ^{14}C Dates
Calendar Years Before Present
Depth Below Sediment Surface (cm)
(d)
Xlf 10^{-6}m^3 kg^{-1}
Accumulation rate (cm yr^{-1})
Calendar Years Before Present

Figure 3

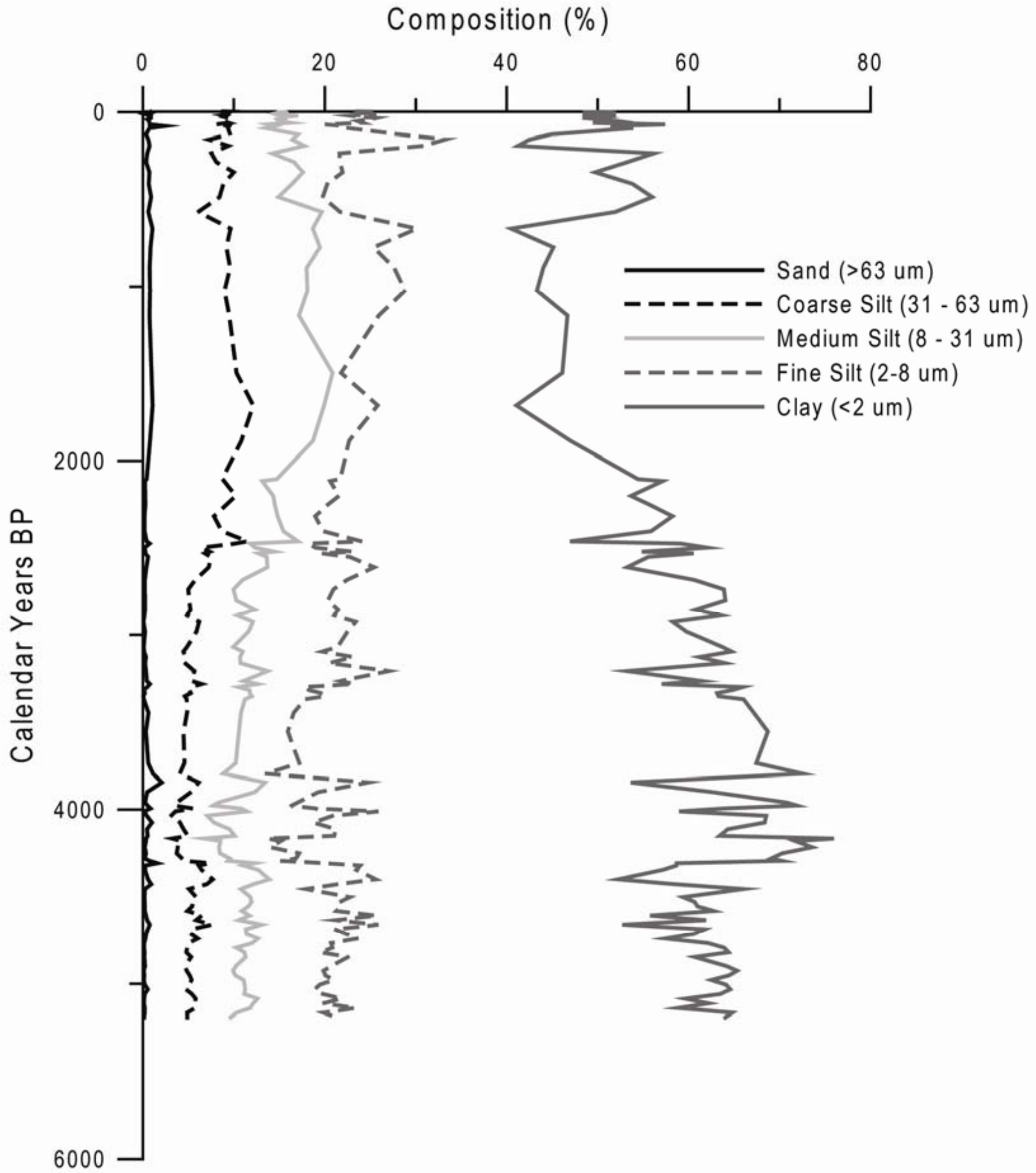
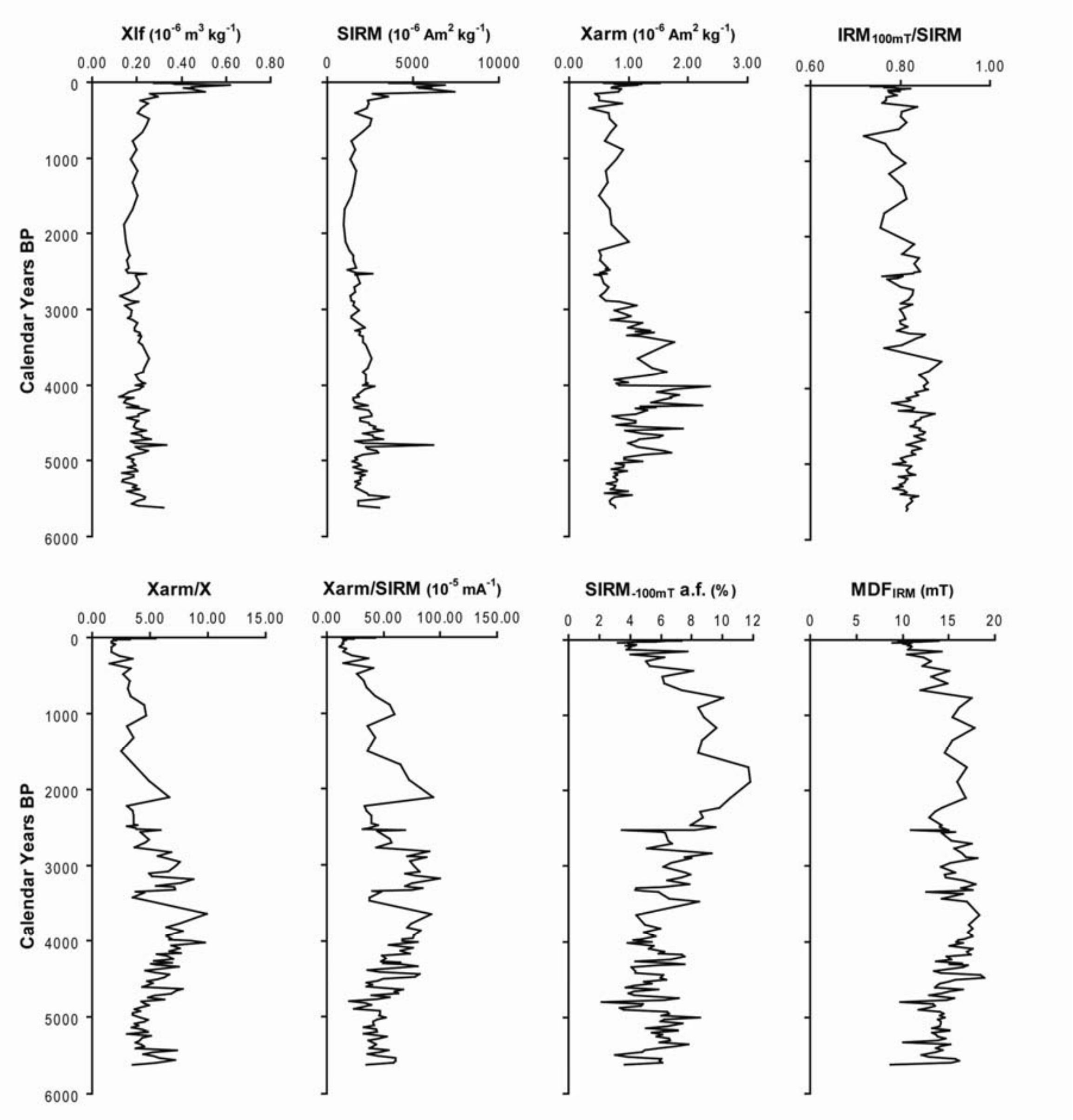

Composition (%)
0
20
40
60
80
0
2000
4000
6000
Calendar Years BP
Sand (>63 um)
Coarse Silt (31 - 63 um)
Medium Silt (8 - 31 um)
Fine Silt (2-8 um)
Clay (<2 um)

Figure 4



Xlf (10^-6 m^3 kg^-1)
0.00 0.20 0.40 0.60 0.80
SIRM (10^-6 Am^2 kg^-1)
0 5000 10000
Xarm (10^-6 Am^2 kg^-1)
0.00 1.00 2.00 3.00
IRM100mT/SIRM
0.60 0.80 1.00
Calendar Years BP
0 1000 2000 3000 4000 5000 6000
Xarm/X
0.00 5.00 10.00 15.00
Xarm/SIRM (10^-5 mA^-1)
0.00 50.00 100.00 150.00
SIRM-100mT a.f. (%)
0 2 4 6 8 10 12
MDFIRM (mT)
0 5 10 15 20
Calendar Years BP
0 1000 2000 3000 4000 5000 6000

Figure 5

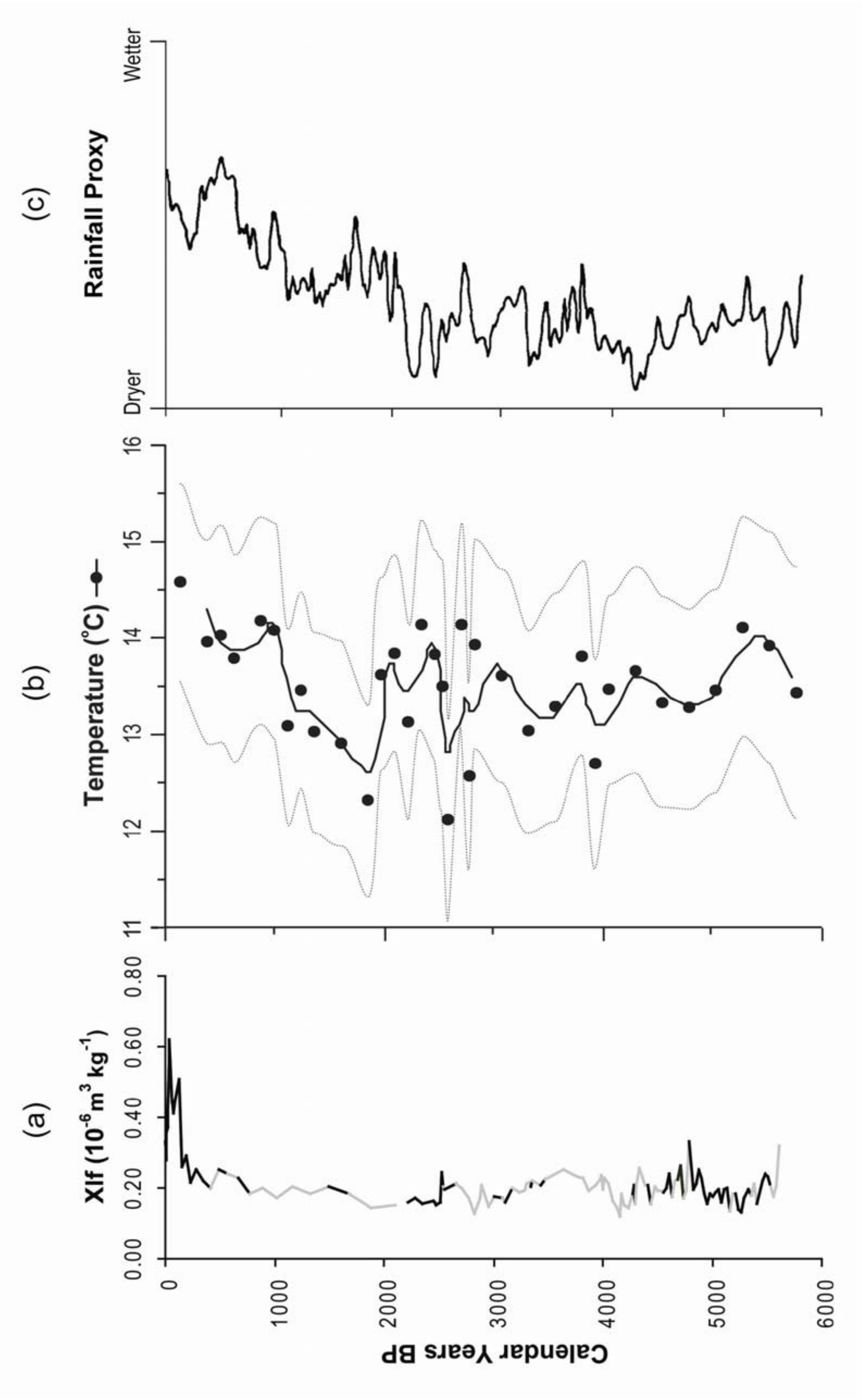

(a)
Xlf (10^{-6} m^3 kg^{-1})
0.00
0.20
0.40
0.60
0.80
(b)
Temperature (°C) —●
11
12
13
14
15
16
(c)
Rainfall Proxy
Dryer
Wetter
0
1000
2000
3000
4000
5000
6000
Calendar Years BP

Figure 6

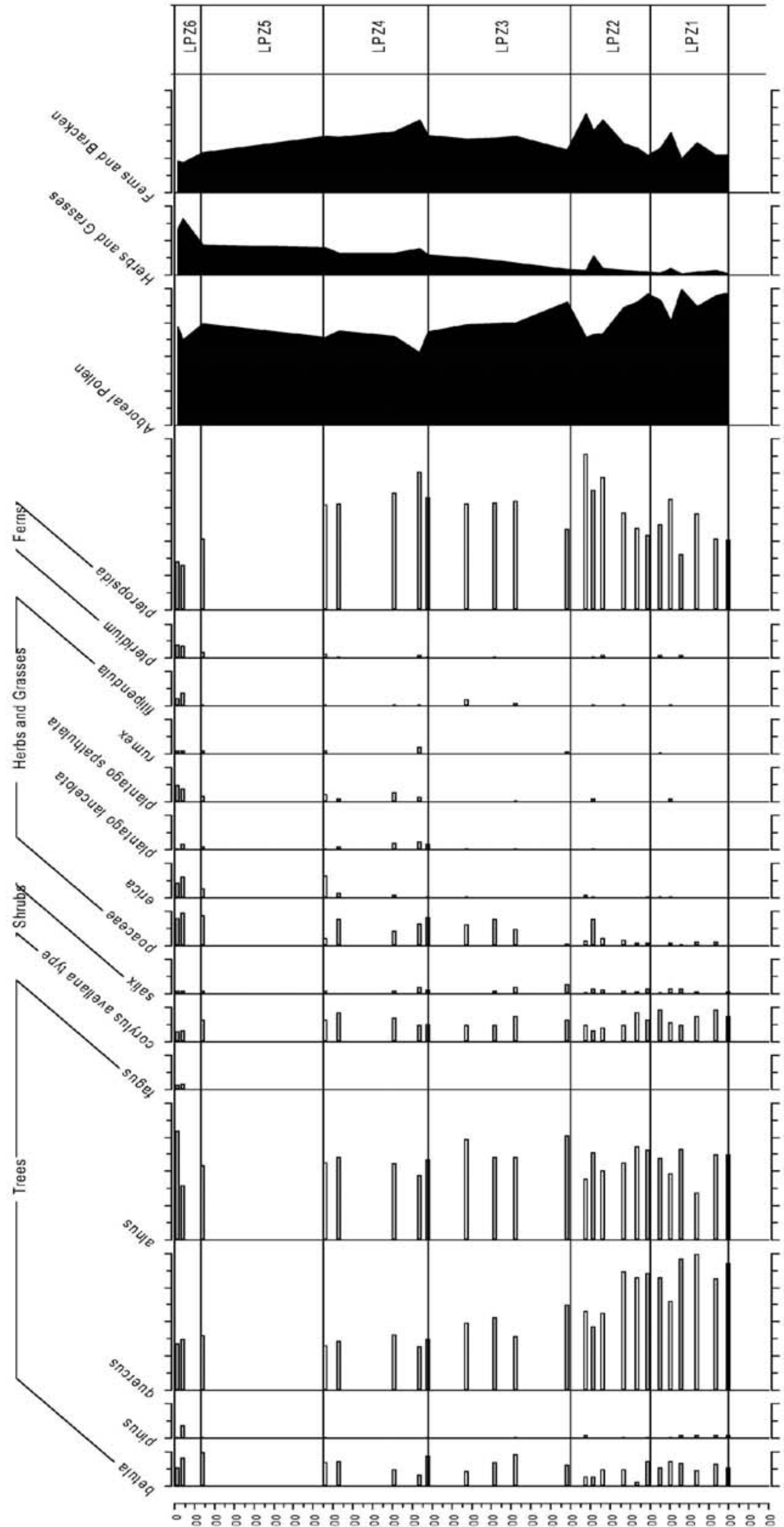

LPZ6
LPZ5
LPZ4
LPZ3
LPZ2
LPZ1
Ferns and Bracken
Herbs and Grasses
Aboreal Pollen
Trees
Shrubs
Herbs and Grasses
Ferns
betula
pinus
quercus
alnus
fagus
corylus avellana type
salix
poaceae
erica
plantago lanceolata
plantago spathulata
rumex
filipendula
pteridium
pteropsida
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
4200
4400
4600
4800
5000
5200
5400
5600
5800
6000

Figure 7

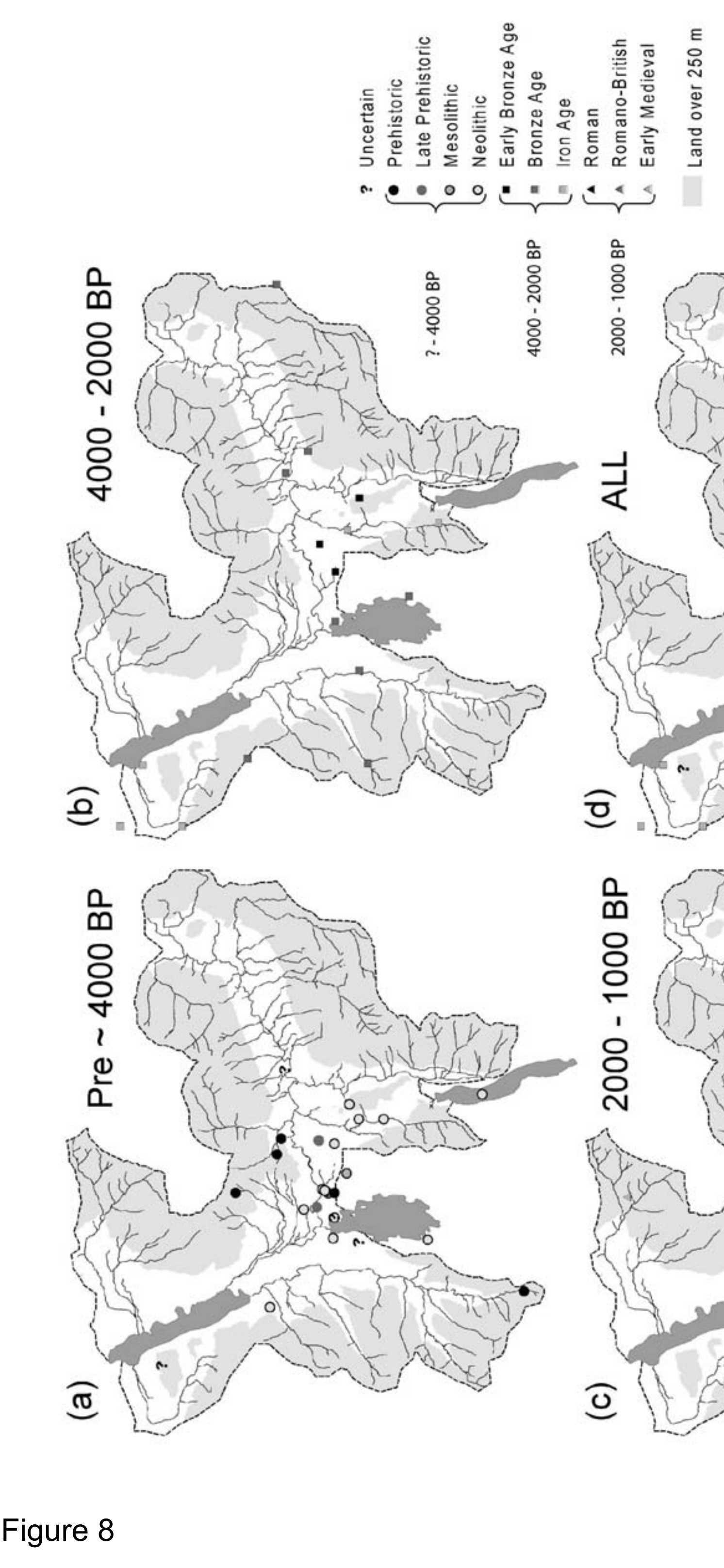

(a)
Pre ~ 4000 BP
(b)
4000 - 2000 BP
(c)
2000 - 1000 BP
(d)
ALL
? Uncertain
● Prehistoric
● Late Prehistoric
⊙ Mesolithic
○ Neolithic
? - 4000 BP
■ Early Bronze Age
■ Bronze Age
■ Iron Age
4000 - 2000 BP
▲ Roman
▲ Romano-British
▲ Early Medieval
2000 - 1000 BP
Land over 250 m

Figure 8