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Evidence for changes in Holocene sediment flux in Semer Water and Raydale, North Yorkshire, UK

R.C. Chiverrell [a,*], F. Oldfield [a], P.G. Appleby [b], D. Barlow [c], E. Fisher [d], R. Thompson [e], G. Wolff [d]

[a] Department of Geography, Roxby Building, University of Liverpool, Liverpool, L69 7ZT, UK
[b] Department of Mathematical Sciences, The University of Liverpool, Mathematical Sciences Building, Liverpool, L69 7ZL, UK
[c] World Wildlife Fund Scotland, Little Dunkeld, Dunkeld, Perthshire PH8 0AD, UK
[d] Department of Earth and Ocean Sciences, 4 Brownlow Street, Liverpool, L69 3GP, UK
[e] School of Geosciences, Crew Building, The King's Buildings, West Mains Road, Edinburgh EH9 3JN, UK

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ABSTRACT

We present preliminary results from studies carried out in the lake and extensively gullied drainage basin of Semer Water in North Yorkshire, England. The results obtained so far are limited by physical problems encountered during coring at the present day lake, the complex nature of the sedimentary infill upstream in Raydale, and difficulties experienced in establishing a continuous Holocene chronology for the site. Both magnetic measurements and organic geochemical analyses show that the bulk of the sediment sampled in Semer Water and in the alluvial area of Raydale, just upstream, is derived from the catchment, although in some cases the allochthonous magnetic signature is overprinted by contributions from bacterial magnetosomes growing in the lake or surface sediments. Significant traces of polyaromatic hydrocarbons (PAHs) in sediments contemporary with the Mesolithic occupation of the Pennines reinforce evidence from elsewhere for the use of fire at this time. Several lines of evidence identify a mid-Holocene period of reduced allochthonous input. Rapid sediment accumulation during the period between 4200 and 3500 cal. BP points to the likelihood of increased erosion during the Bronze Age. Geomorphological studies point to periods of alternating dissection and aggradation in the catchment during the last 2000 years. The record presented gives some indication of the potential for uniting geomorphological, palaeolimnological and organic geochemical research in an effort to trace the Holocene evolution of a complex, highly eroded system.

1. Introduction

The differing goals of fluvial geomorphologists and palaeolimnologists generally lead to differences in site selection. In the former case, dynamic systems with discontinuities, regime shifts and sharp contrasts in sediment characteristics and spatial disposition through time hold most fascination. In the latter, the emphasis is usually on continuity and conformable sediment accumulation in relatively low energy sinks. Linking the complementary perspectives on past environmental change by uniting both strands of research is clearly a desirable aim, although studies that address this are relatively rare (e.g. Foster et al., 2003; Chiverrell, 2006). Working in contexts that hold some promise of satisfying the goals of both research communities poses special challenges. One such environment is considered here. The results presented draw on a much larger body of data contained mainly within PhD theses by Barlow (1998) and Fisher (1999), the former dealing with particulate flux using mainly magnetic measurements, and the latter concentrating on organic geochemistry. The main focus here is on those aspects of the research that have implications for reconstructing allochthonous sediment sources and catchment processes. There is also reference to the logistic hurdles encountered, and on the prospects that the study site holds for future research uniting geomorphological and palaeolimnological approaches.

2. The site

Semer Water (3°01.6′W; 54°14.2′N; National Grid Reference SD 331828), lying at 215 m a.s.l., has a surface area of some 0.27 km^2 and receives drainage from three headwater tributaries, Bardale Gill, Raydale Beck and Cragdale Water (Fig. 1). The catchment of 43.6 km^2 rises to over 600 m at its highest point. The maximum extent of the lake during the late Holocene has not been established, but is likely to have exceeded 0.6 km^2. During the period considered, the catchment to lake ratio thus probably varied from around 70:1 to over 160:1. The lake's reduced size is due, in part at least, to a lowering of level in 1939–1940 when the outflow was deepened. Squance (1980) ascribes the depression within which Semer Water lies to the slumping, burial and subsequent melting of an ice block at the front of a glacier in Wensleydale, to the north, during deglaciation from the last glacial maximum. The lake drains in that direction via the River Bain which

* Corresponding author. Tel.: +44 151 7942846.
E-mail address: rchiv@liv.ac.uk (R.C. Chiverrell).

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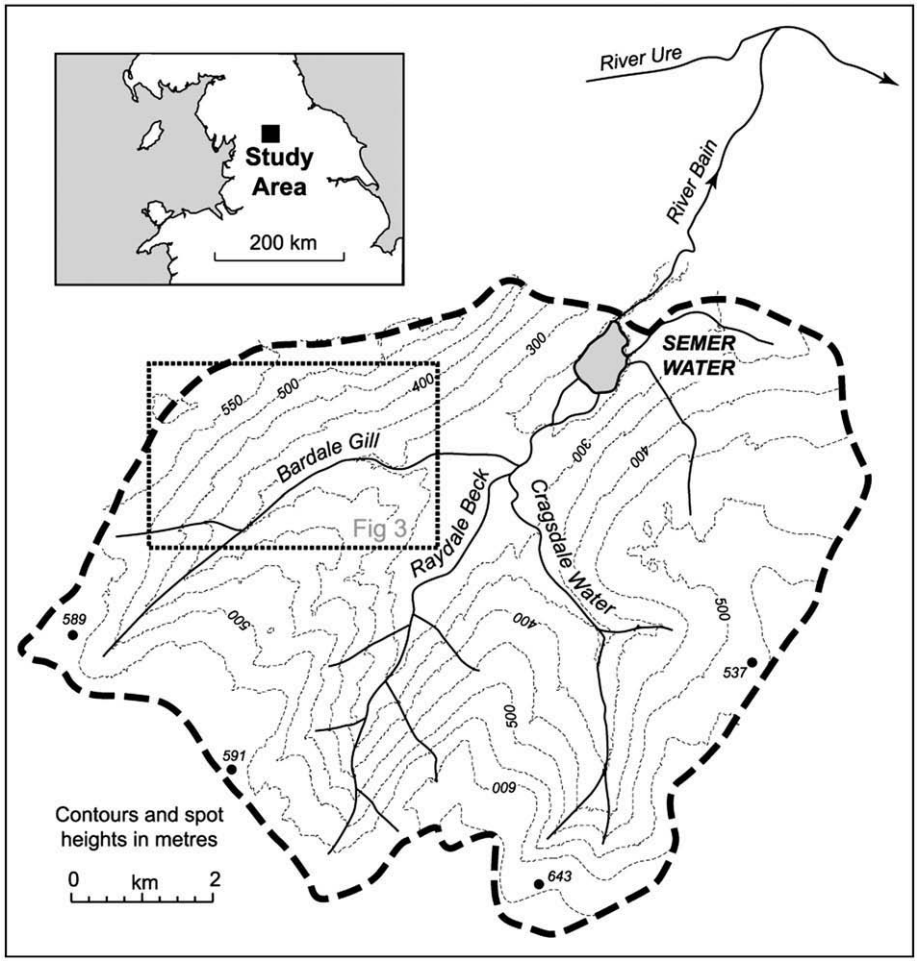

Fig. 1. Location and relief of the Semer Water catchment. Outline box defines the extent of Fig. 3.

cuts through glacial moraine impounding the lake. The three inflowing streams focus a highly developed drainage net into the head of Raydale, to the south of the present day lake (Fig. 1).

The Upper Carboniferous limestones, shales and sandstones that underlie the catchment are extensively covered by glacial diamicts. There appears to have been only limited para- and periglacial remobilisation of these diamicts, with much of the glacial sediments in the Raydale basin probably being an *in situ* fill and showing little of the surface morphology, sediment fabric and stratification commonly associated with soliflucted diamicts. Since deglaciation, the rivers have incised into the glacial deposits, giving rise to a series of fluvial landforms, river terraces and alluvial fans. At higher elevations, gentle slopes and summits are covered by blanket peat which is extensively eroded, often to the underlying bedrock. Where limestone crops out there are sinkholes, as along the western flank of the catchment. The Raydale valley bottom is covered by alluvium of mixed fluvial and lacustrine origin. Fig. 2 summarises the main features of the catchment geology. Over 90% of the catchment is grazed or used for hay/silage and less than 5% is woodland, mainly sitka spruce planted between 1966 and 1970 (Barlow, 1998). Mean annual rainfall is of the order of 1400 mm yr^{-1}.

3. Research methods

3.1. Catchment sampling for magnetic measurements

Forty-two samples were taken from sites in the lake catchment to characterise the properties of the sediment sources. All were measured for a range of magnetic properties: bulk, low field susceptibility (χ), anhysteretic remanent magnetization (ARM), isothermal remanent magnetization at 100 mT (IRM_{100}) and saturation isothermal remanent magnetization (SIRM) using a field of 1 T. The quotients ARM/SIRM, ARM/ χ and IRM_{100}/SIRM were also derived.

3.2. Bardale Gill: geomorphological mapping and palaeosol sampling

The fluvial landforms within the Bardale Gill tributary were studied to ascertain the postglacial geomorphic evolution of the catchment. The reach mapped (Fig. 3) extends up valley from the waterfall nick point just downstream of the Hebden Fold Gill tributary junction to the heavily eroded, peat-covered headwaters of Fleet Moss (see Fig. 2). Bardale Gill has cut a gully, which in places is 50 m across, into the glacial deposits intermittently exposed on both sides of the river. The river terraces and alluvial fans within this reach were mapped and the sediments described using available exposures. At three locations, two alluvial fans and one river terrace, soils were encountered buried beneath fluvial gravels. Radiocarbon assays from such soils (Table 1) provide information about the age of underlying and overlying deposits (Harvey, 1996). Here we have dated the top horizon of the soil and targeted the humic acid fraction of the soil organic matter. The humic acid fraction produces younger age estimates for a buried soil than other fractions, e.g. the humin fraction (Matthews, 1993), and provides a 'younger than' estimate for the overlying sediments (Harvey, 1996). Throughout the paper, all new dates presented list the original radiocarbon age determination in ^{14}C years BP, and these are listed in Table 1. These dates and others from the published research are presented as the 1-sigma calibrated age range in years BP, with all radiocarbon determinations calibrated to calendar years BP by the authors using CALIB 5.0.1 (Stuiver et al., 2005).

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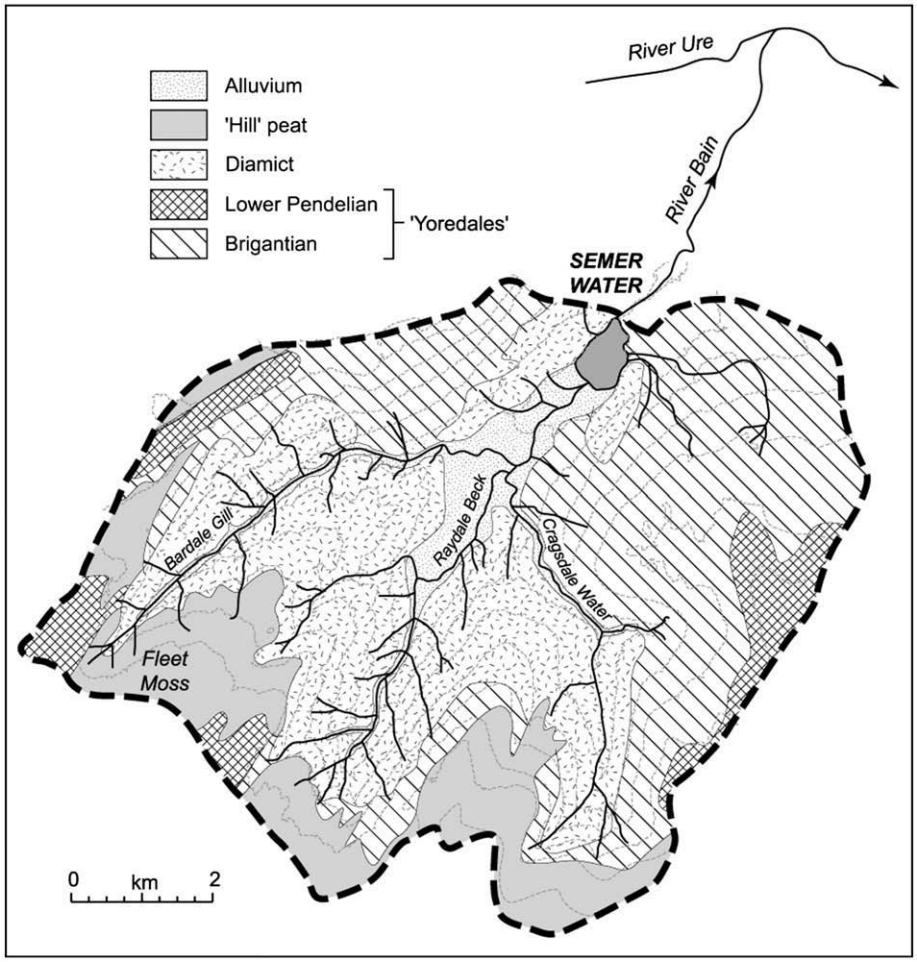

Fig. 2. Semer Water: simplified bedrock and Quaternary geology. The river outline also identifies the length and distribution of hillslope gully systems.

3.3. Semer Water

The lake sediments were sampled using both a Mackereth minicorer that preserves an undisturbed sediment water interface, and a 6 m Mackereth corer. The 18 minicores obtained from water depths ranging from 1.5 to 10.5 m, each provided between 55 cm and 85 cm of late Holocene sediment. Three cores, T3 and two taken close to SL2 (Fig. 4) were analysed for ^{210}Pb and ^{137}Cs using gamma spectrometry (Appleby et al., 1986). All the minicores located in Fig. 4, were subsampled for magnetic measurements. χ and ARM were measured in all cases, the full range of measurements in two (cores 6 and 10), as well as in both of the longer Mackereth cores. Core T3 was used for organic geochemistry. It was subsampled at 2 cm intervals (45 samples in total) and each sample was analysed for C, H and N so that total organic carbon (TOC) content and C/N ratios could be established. Lipids were extracted (Fisher, 1999; Fisher et al., 2003) from the sediments using organic solvents (23 samples in total; 2 cm intervals for the top 20 cm, 4–10 cm intervals below). Some lipids have specific biological origins and are referred to as biomarkers. These were used to determine the source of organic matter to the lake sediments. One additional 80 cm-long minicore from the deepest part of the lake was subdivided into 20 cm lengths; the 4 subsamples were then separated into particle size fractions ranging from <1 μm to >64 μm and each fraction subjected to magnetic measurements using the dispersal, granulometric and magnetic measurement procedures summarised in Yu and Oldfield (1993).

The two attempts to secure 6 m cores from the deepest part of the lake (SL1 and SL2 in Fig. 4) recovered only 2.2 m and 2.4 m of sediment, respectively, before the core tube reached densely compacted, impenetrable sediment. Two AMS radiocarbon dates were obtained on the shorter core of the two cores and three on the longer (Table 1).

3.4. Raydale

Thirty-two gouge cores and 3 Giddings cores were obtained from Raydale (Fig. 4). Giddings core A and C confirmed that as far as 1.3 km beyond the southern edge of the current lake, over 10 m of partially lacustrine Holocene sediments were present. The two gouge cores, shown in Fig. 4, confirm that the depth of fill some 400 m from the southern edge of the lake was in excess of 18 m. Further information on the extent of the alluvial/lacustrine infill was obtained from a suite of 13 resistivity profiles. Occasional peat lenses were observed in section in the main river channel, but not sampled.

Only the three Giddings cores were subsampled for analysis. Preliminary scans of a few samples from each core were carried out with a view to identifying the main pollen types and constraining the chronologies. In addition, Core A, close to the position of the main inflowing stream, was used for organic geochemical analysis (30 samples at ~30 cm resolution), magnetic measurements and granulometry, Core C, less than 200 m to the east was used for radiocarbon dating, magnetic measurements and granulometry, and Core B, some 600 m to the north, was used for magnetic measurements and granulometry.

4. Chronological problems

Two of the ^{210}Pb and ^{137}Cs profiles from Semer Water showed clear evidence for discontinuities in sedimentation (Fig. 5). These appear to

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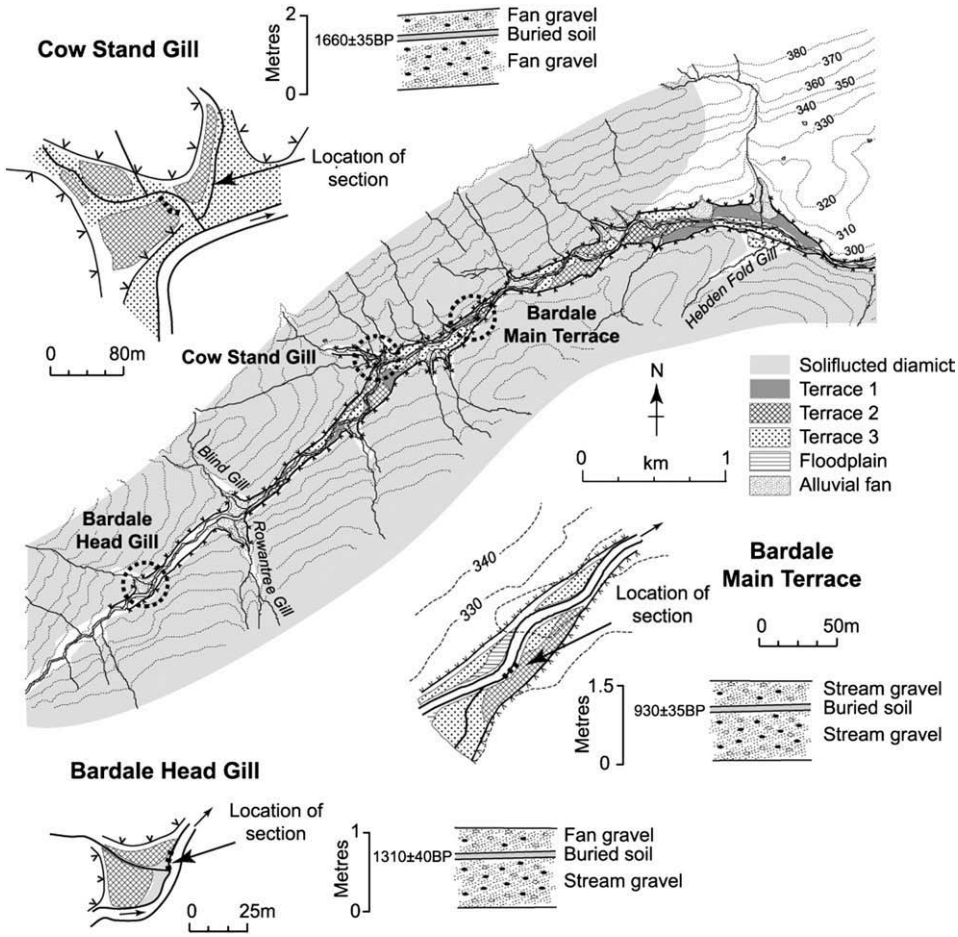

Fig. 3. Geomorphology of Bardale. Inset diagrams show the geomorphology, stratigraphic sections and radiocarbon dating of the alluvial fans at Cow Stand Gill and Bardale Head Gill, and the main river terrace.

have arisen from either a hiatus in accumulation or the intercalation of older material with no ^{137}Cs or unsupported ^{210}Pb. In a third core, dated as part of a survey carried out by the Environmental Change Research Centre, University College London, there was an apparent hiatus at 25 cm. The mean sedimentation rate above this hiatus was estimated as 0.23 cm per year from both the ^{137}Cs and ^{210}Pb profiles. Both of the ^{137}Cs profiles

Table 1
Radiocarbon dates obtained for Bardale, Semer Water and Raydale

Site	Context	Method	Lab code	^{14}C date cal. BP	2σ range
Sections in Bardale					
Main terrace	Top of buried soil	AMS humic acid	SUERC-7503	930±35BP	770–930
Cow Stand Gill	Top of buried soil	AMS humic acid	SUERC-7502	1660±35BP	1420–1690
Bardale Head Gill	Top of buried soil	AMS humic acid	SUERC-7501	1310±40BP	1170–1305
Semer Water cores					
Core SL 1	Twig at 40 cm	AMS	AA-26406	Post-1950	
Core SL 1	Root at 65 cm	AMS	AA-26407	Post-1950	
Core SL 2	Twig 10–20 cm	AMS	AA-25554	Post-1950	
Core SL 2	Twig 100–110 cm	AMS	AA-25555	260±60	0–421
Core SL2	Twig 180–200 cm	AMS	AA-25556	460±45	492–523
Raydale cores					
Giddings C	Wood 225 cm	AMS	AA-25541	4305±65	4831–4872
Giddings C	Wood 380 cm	AMS	AA-25542	3350±60	2474–3681
Giddings C	Wood 455 cm	AMS	AA-25543	3340±60	3472–3663
Giddings C	Wood 500 cm	AMS	AA-25544	3480±65	3637–3833
Giddings C	Wood 580 cm	AMS	AA-25545	3565±55	3730–3912
Giddings C	Wood 795 cm	AMS	AA-25546	3670±60	3893–4085
Giddings C	Wood 805 cm	AMS	AA-25547	3815±95	3998–4403
Giddings C	Wood 830 cm	AMS	AA-25548	4165±65	4564–4830
Giddings C	Macro.855 cm	AMS	AA-25549	3885±50	4158–4411
Giddings C	Wood 869 cm	AMS	AA-25550	3725±55	3939–4144
Giddings C	Wood 897 cm	AMS	AA-25551	3785±55	4009–4235
Giddings C	Macro.1000 cm	AMS	AA-25552	3760±50	3993–4222
Giddings C	Wood 1017 cm	AMS	AA-25553	3740±65	3983–4221

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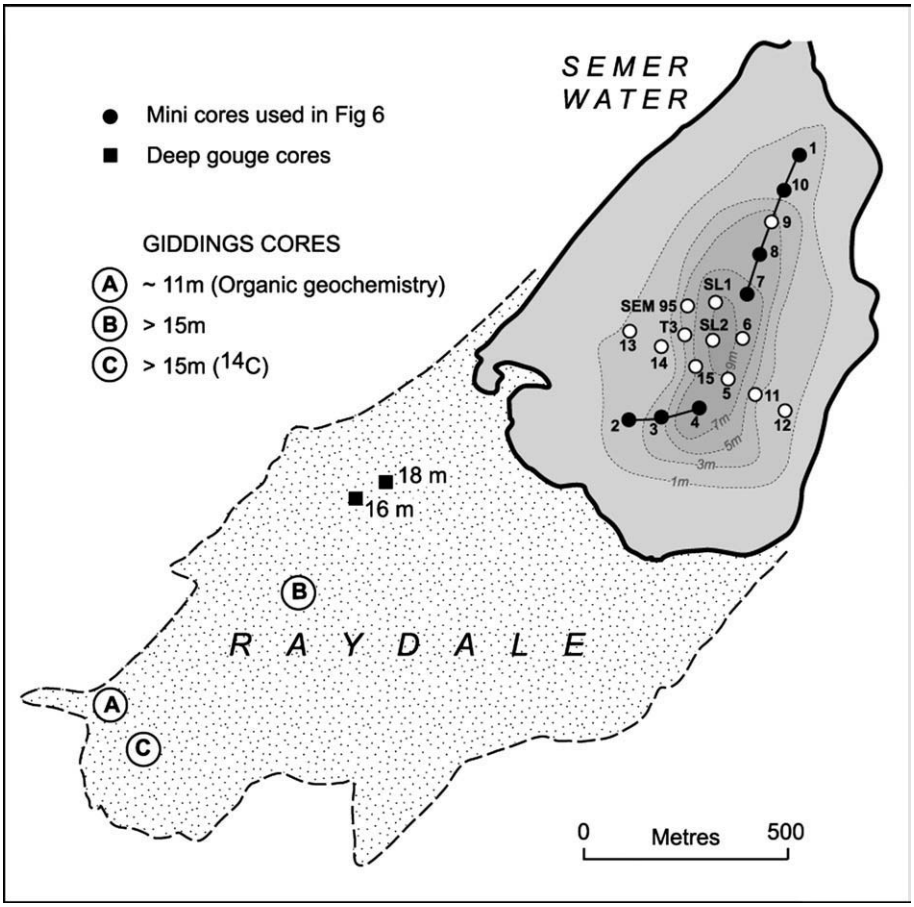

Fig. 4. Bathymetry and main coring locations in Semer Water and Raydale. Cores SL 1 and 2 were taken using a Mackereth 6 m corer. The remaining cores were taken using a minicorer. Solid circles mark the location of cores shown in Fig. 8; with cores 2, 3 and 4 forming group A, and 1, 10, 8 and 7 forming group B of these magnetic profiles. The susceptibility trace for core 9 appeared to be anomalous and was excluded from Fig. 8.

taken as part of the present project show clear 1963 peaks, and one shows the 1954 onset of deposition between 20 cm and 15 cm.

Of the 5 AMS ^{14}C dates (Table 1) obtained from the longer cores, three, ranging in depth from 10 cm to 65 cm were post AD 1950 in age; one from 100–110 cm had calibrated age range from 0 to 421 BP; and only one, based on a twig at 180–200 cm in Core 2 and dated to 492 523 cal. BP can be used to provide any estimate of the mean sedimentation rate. This appears to imply an average of c. 0.36 cm per year over the last c. 550 years. The combination of ^{14}C, ^{210}Pb and ^{137}Cs

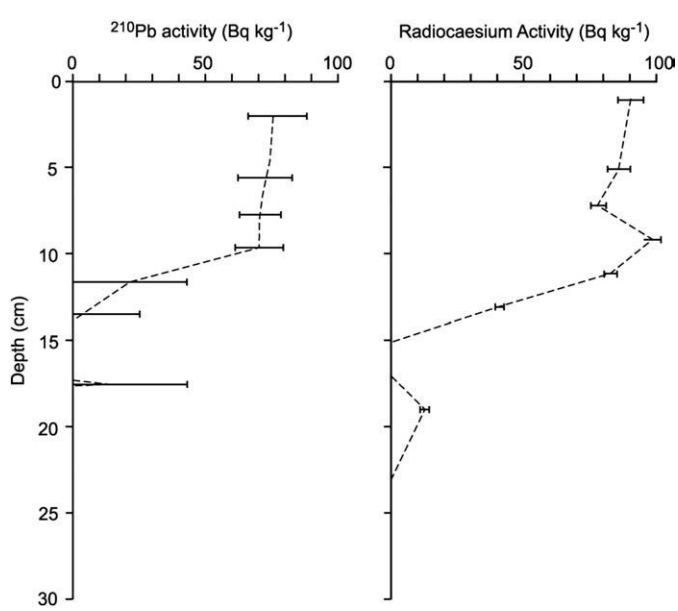

Fig. 5. ^{210}Pb and ^{137}Cs activity profiles from Semer Water core T3 (Fig. 4).

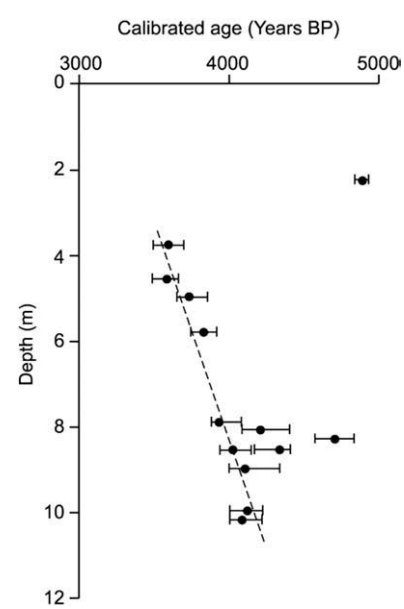

Fig. 6. Calibrated ages and 1σ ranges for the AMS radiocarbon dates obtained for Raydale Giddings Core C. ^{14}C Dates were by the authors using CALIB 5.0.1 (Stuiver et al., 2005).

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data for the second half of the 20th century thus point to accumulation rates ranging from around 0.2 cm to >1 cm per year. Beyond these estimates, and the observation that rates varied dramatically within and between cores and breaks in sedimentation were frequent, no further conclusions may be adduced from these radiometric measurements.

The results of the 13 ^{14}C determinations on wood and terrestrial macrofossil material from part of Giddings Core C (Table 1) are shown in Fig. 6. They span just over 6 m of depth. Only if the more recent dates for each section of the core are accepted as being based on material contemporary with sediment accumulation do these provide the basis for a chronology. In this regard, it should be borne in mind that in an eroding catchment that includes peat-covered areas and has yielded predominantly allochthonous organic matter, not all the organic macrofossil material will be contemporaneous with the time of deposition. Using nine of the dates and omitting those that definitely relate to old inwashed terrestrial material, we obtain an age span of around 600 years for the sediments between 10.1 m and 4.3 m, giving a mean sedimentation rate at the coring site of just under 1 cm per year.

Pollen analyses (Fig. 7) carried out on 9 to 11 samples from each of the Raydale Giddings Cores (Barlow, 1998) have been used conservatively here to provide only very limited constraints on chronology. The earliest sample in Core A, at 9.1 m shows *Pinus*, *Betula* and *Corylus* as the main forest taxa. Both *Ulmus* and *Quercus* are continuously present but *Alnus* is not recorded. An age of between 9800–9300 and 8500–8200 cal. BP is likely, based on calibration of radiocarbon dates obtained for nearby sites presented by Bartley et al. (1976, 1990). The 1.5 m of sediment sampled below this for the earliest organic geochemical analyses thus date from the early Holocene. The depth of the Holocene fill made it impossible to retrieve late Devensian material in this core.

The first signs of an *Alnus* increase are recorded at 5.65 m in Core A (Fig. 7), pointing to an age of around 8500–8200 cal. BP (Bartley et al., 1976, 1990; Turner et al., 1973). The topmost sample, at 0.6 m, appears to postdate the *Ulmus* decline at c. 5900–5700 cal. BP (Bartley et al., 1990).

The whole of Core B postdates the *Alnus* rise (Fig. 7). The base clearly pre-dates the *Ulmus* decline, and the highest analysed sample at 3 m postdates it. The whole of Core C (Fig. 7), from 13.5 m upwards, postdates the *Ulmus* decline, which is consistent with the ^{14}C dates from between 10.17 m and 2.25 m already noted (Fig. 7). Thus, although at least the bottom 6 m of Core A fall within the first half of the Holocene, the whole 14 m of Core C some 100 m to the east, postdates 6000 BP.

In summary, Core A spans the period from the early Holocene to some time after 6000 BP: Core B spans the period from 6–7000 BP at

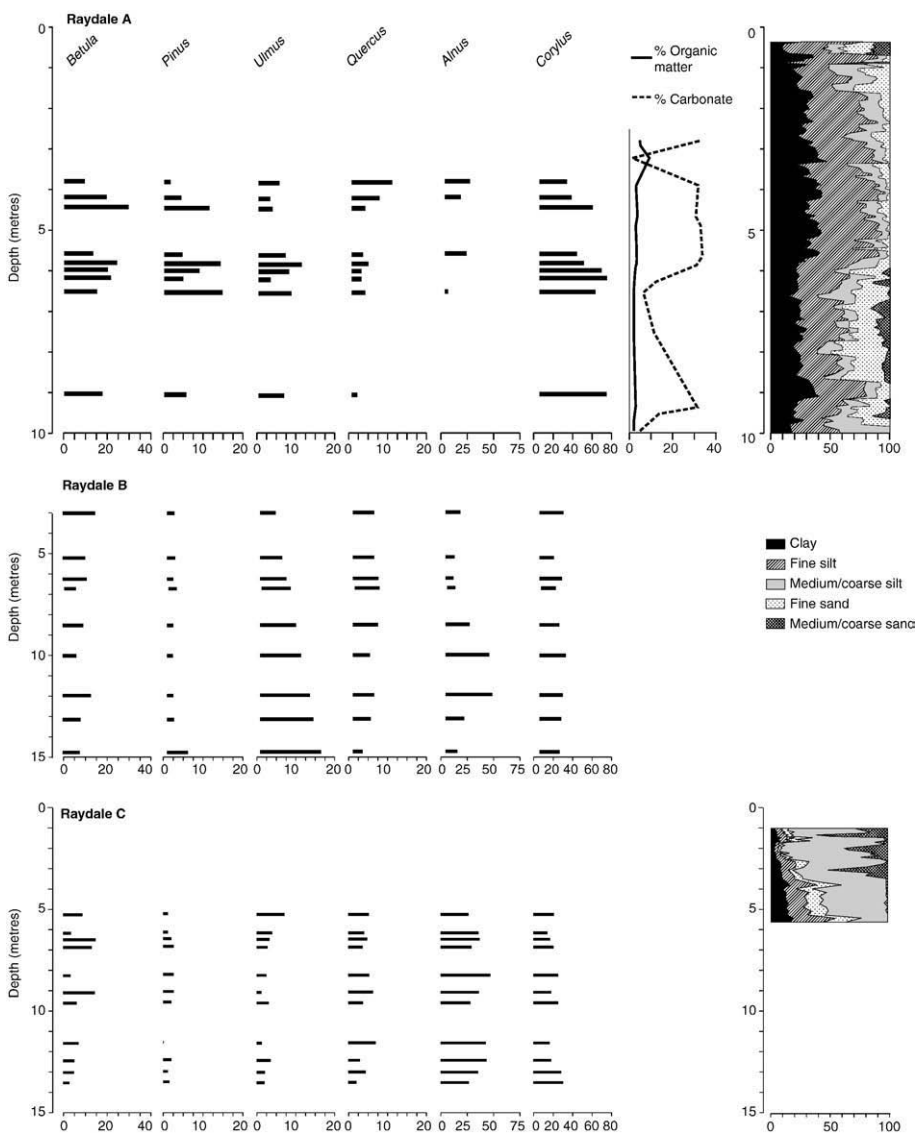

Fig. 7. Selected taxa pollen data for Raydale Giddings core A, B and C, alongside % organic matter and carbonate curves for Giddings core A, and granulometry profiles for Giddings core A and C.

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the base, to some unknown date post-6000 BP at the top; the base of Core C postdates 6000 BP and its top postdates 3500 BP.

5. Landform evolution in Bardale Gill

The fluvial reach contains three levels of river terrace and several tributary alluvial fans (Fig. 3). The first and highest terrace is present in two locations, comprises coarse fluvial gravel, and is covered by soils of some maturity (Harvey et al., 1984). The second terrace is more widespread, also comprises fluvial gravel, but the overlying soil is thinner and appears less mature. Sections exposed in the Bardale second terrace (Fig. 3) reveal two units of alluvial gravel separated by a buried brown earth soil some 10 cm in thickness. Radiocarbon dating of the humic acid fraction of the uppermost layers of this soil yielded a date of 770–930 cal. BP (930±35 BP: SUERC-7503) (Table 1). The third, and lowest, river terrace describes a suite of landforms that is younger than the second terrace, but varies in character from fairly mature features sustaining thin soils to recently vegetated point-bars and abandoned channels.

Feeding into the valley there are a series of gullies cut into the glacial sediments, and where these tributaries meet the axial stream, alluvial fans have formed. At Cow Stand Gill the alluvial fan is a complex multiple phase landform, with two surfaces. The deposits of the older surface are exposed (Fig. 3), and the sequence shows two units of alluvial fan gravels separated by a 15 cm-thick brown earth soil. This fan surface grades to the second river terrace. The uppermost layers of the soil were sampled for ^{14}C dating, and the humic acid fraction yielded a date of 1690–1420 cal. BP (1660±35 BP: SUERC . The alluvial fan at Bardale Head Gill also comprises two phases of fan formation, and here the younger, lower surface has exposure that shows two units of alluvial fan gravel separated by a 5 cm-thick soil. The humic acid fraction of this soil has been dated to 1305–1170 cal. BP (1310±40 BP: SUERC-7501).

The sequence of events in the postglacial evolution of the Bardale Gill is resolved, in the present study, into two broad phases. During the late glacial and early Holocene the river incised, either gradually or rapidly, after which there was a considerable period of stability. The first river terrace is a remnant feature, the gravels of which were probably lain down during late glacial or early Holocene times. The thickness of soil overlying this feature implies abandonment and incision probably during the early to mid-Holocene, and it pre-dates the lower gravels of the higher fan surface at Cow Stand Gill dated to before 1690–1420 cal. BP. During the late Holocene the river experienced cycles of aggradation and incision, with phases of gravel aggradation associated with the second and third suite of terraces dated. Dating of the second terrace deposits indicates phases of gravel aggradation before and after a period of stability that ended after 930 770 cal. BP. It has not been possible to secure the timing of the onset of gullying in the tributary systems, with gravel aggradation associated

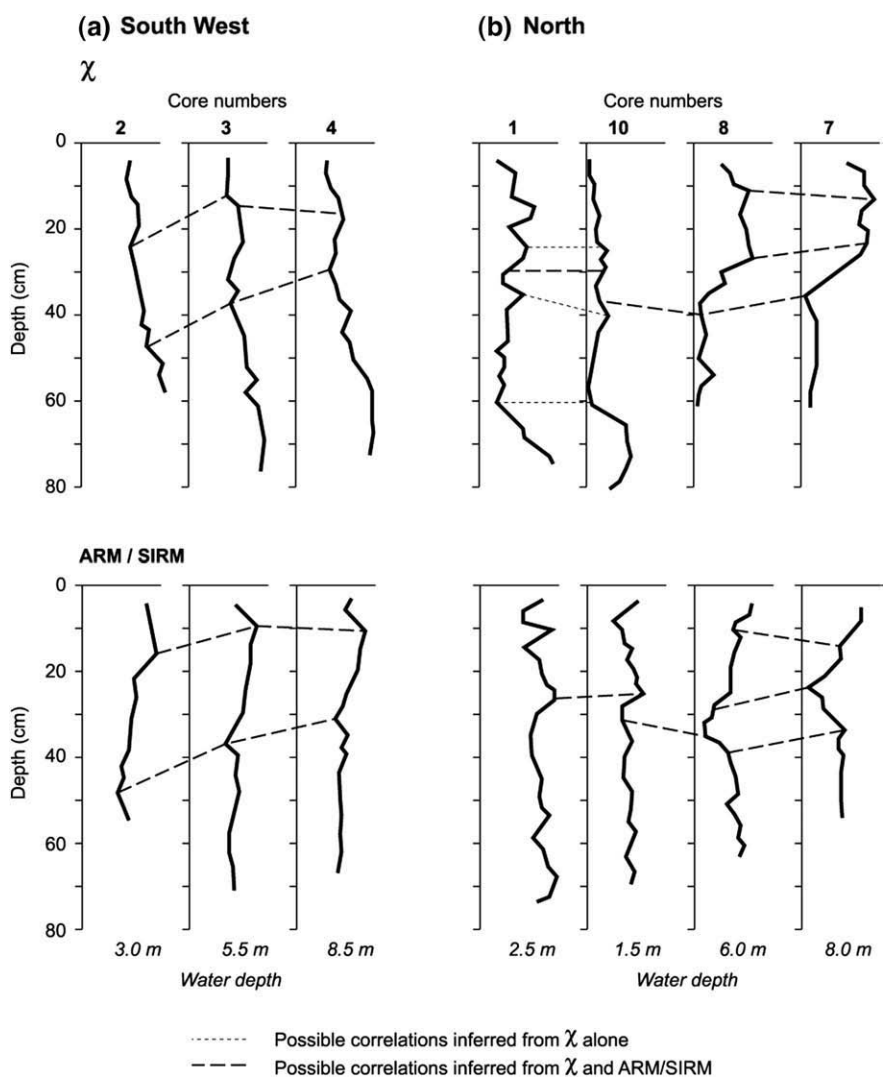

Fig. 8. Magnetic susceptibility (χ) and ARM/SIRM profiles for 10 of the cores (Group A and B) identified on Fig. 4. They are grouped into sets from the south-western (A) and northern (B) areas of the lake. Tentative correlation lines have been marked, with the bolder ones supported by trends in both χ and ARM/SIRM.

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with the higher fan terrace before 1690–1420 cal. BP at Cow Stand Gill. The phase of relative stability represented by soil accumulation was followed by further gravel aggradation, again associated with the higher fan terrace, after 1690–1420 cal. BP. The surface of this alluvial fan terrace appears to grade to the second river terrace, which is suggestive of some equivalence between these landforms. The Cow Stand Gill gully system has incised into the higher fan terrace producing a lower surface that grades to the third river terrace, which clearly postdates 930–770 cal. BP. Geochronological control for the alluvial fan sequence at Bardale Head Gill is only available for the deposits of the lower fan surface, and so the onset of gully incision clearly pre-dates 1305–1170 cal. BP, and there is evidence for renewed alluvial fan development after that date.

6. Analytical results

6.1. Magnetic measurements

Fig. 8 shows plots of χ and ARM/SIRM based on measured subsamples at 2–3 cm depth intervals from 7 of the Semer Water minicores. They are grouped into two sets, each of which is separately identified in the location map. Within each set, lines have been drawn linking horizons for which correlations are supported by each of the independently derived magnetic properties. There are indications that deposition was reasonably conformable over each of the two transects. Difficulty in correlating magnetic profiles from the remaining cores, including those from deeper water in the centre of the lake, is consistent with the problems encountered in interpreting the radiometric data from this part of the lake (see above).

Fig. 9 summarises the results of susceptibility and remanence measurements on samples from the catchment and from the lake and Raydale cores. The bi-variate plots show the extent to which the envelope of values for each set of sediment core measurements lies within or extends beyond the range of values for the catchment samples. The lake sediment samples generally have higher ARM values relative to both χ and SIRM than do the catchment samples. Moreover, values for ARM and ARM/SIRM in all the cores, save Core C, from Raydale include the majority of samples that lie outside the catchment envelope. These features show that most of the lake sediments and those from Raydale Cores A and B have a significant magnetite contribution from magnetosomes produced by magnetotactic bacteria growing within the lake or surface sediments (cf. van der Post et al., 1997; Oldfield and Wu 2000; Oldfield et al., 2003) and producing mainly stable single domain magnetite with a disproportionately high ARM (Maher, 1988). On the other hand, most of the catchment samples have a 'harder' isothermal remanence mainly attributable to a higher contribution from haematite. This reflects the extent to which catchment sampling included material from subsoils and unweathered parent material.

Fig. 10 compares the values for ARM/χ, ARM/SIRM and $IRM_{100\ mT}$/SIRM in the mid-Holocene part of Giddings Core A (below) and the ^{14}C-dated (c. 4200–3500 cal. BP) part of Core C (above) with catchment values for the same quotients. These plots reinforce the conclusion that only in the case of Raydale Core C do the magnetic measurements reflect allochthonous input that has not been significantly modified by the addition of bacterially derived magnetite.

6.2. Organic geochemistry (Fig. 11)

In the present account, inferences regarding organic matter (OM) provenance have been based on the evidence and interpretations discussed more fully by Fisher et al. (2003) and the sources quoted therein.

C/N ratios in Raydale Giddings Core A range from 12–19. This suggests that the dominant source of OM is from catchment-derived vascular plants. The biomarkers are also dominated by indicators of allochthonous OM, e.g. ω-hydroxy acids, pentacyclic triterpenoid alcohols and ketones, C_{29} sterols and HMW fatty acids. However, the relative concentrations of biomarkers vary considerably down-core:

In the deepest sediments (9.5–10.5 m) the biomarkers are entirely dominated by indicators of allochthonous inputs (Fig. 11a). Autochthonous biomarkers were not detected in these sediments. The sediments also contain high concentrations (0.4 mg/g TOC) of polycyclic aromatic hydrocarbons (PAHs). These form when wood, or, in modern times, coal or petroleum is burnt under oxygen deficient conditions (Baek et al., 1991). Those present in the highest concentrations in Raydale sediments are phenanthrene, benzo(b)fluoranthene, dibenz(ah)anthracene, chrysene, benzo(ghi)perylene and pyrene. The concentration of PAHs falls to 0.05 mg/g TOC at the top of this zone (9.5 m). There is also a gradual change in the mean carbon number (MC#) of the *n*-alkanes (from 29.25 to 28.25) suggesting that a change may have occurred in the source of the organic matter, from peat and grassland to woodland, consistent with the development of forest cover during the early Holocene.

From 7–8.5 m (Fig. 11a), the concentration of allochthonous biomarkers is virtually undetectable. However, there is an increase

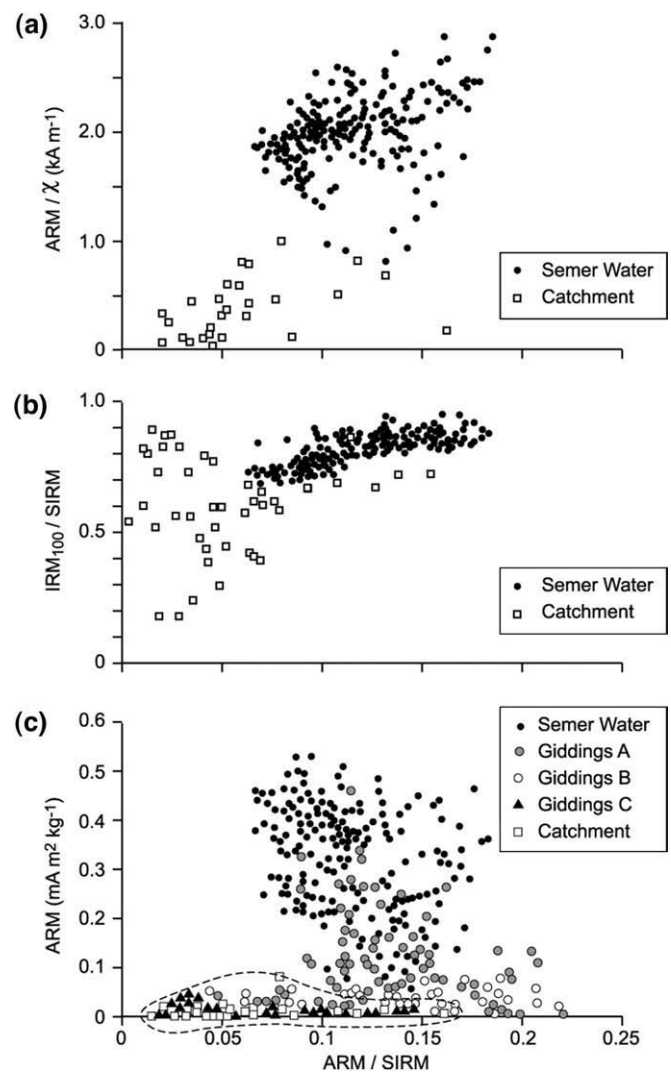

Fig. 9. Biplots of magnetic properties in the sediment cores and catchment samples from Semer Water and Raydale. The upper two graphs compare the Semer Water and catchment properties. Note the generally higher ARM/SIRM and especially ARM/χ quotients in the sediments in (a) and the much wider scatter and generally much lower values of $IRM_{100\ mT}$/SIRM in (b) and (c) also includes quotients from the three Raydale Giddings cores. All but the values from Core C show ARM values well outside the catchment envelope.

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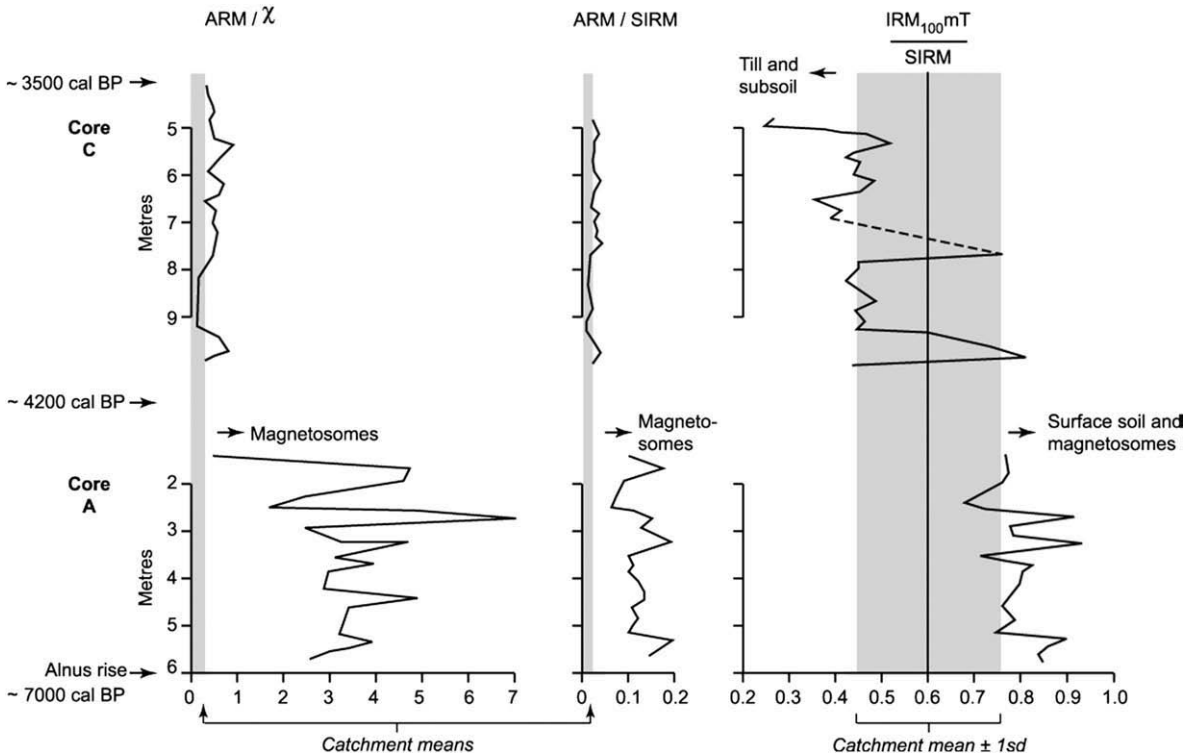

Fig. 10. Down-core traces of ARM/χ, ARM/SIRM and $IRM_{100\ mT}$/SIRM for parts of Raydale Giddings Cores A (below) and C (above) compared with the mean values for catchment samples shown as grey shading. In all cases, high quotient values are likely to reflect a stronger contribution from bacterial magnetosomes and/or surface soils. The lower values are typical of catchment subsoils and parent material. They reflect the high content of haematite in these materials.

in the relative concentration of bacterial indicators (e.g. β-hydroxy acids and *iso* and *anteiso* acids). The sediments are also characterised by high concentrations of PAHs (0.4 mg/g TOC). The MC# of the *n* alkanes is very variable and ranges from 28 to 29.6. This suggests that both forested and unforested parts of the catchment contributed organic matter to the sediments during this period. The changed

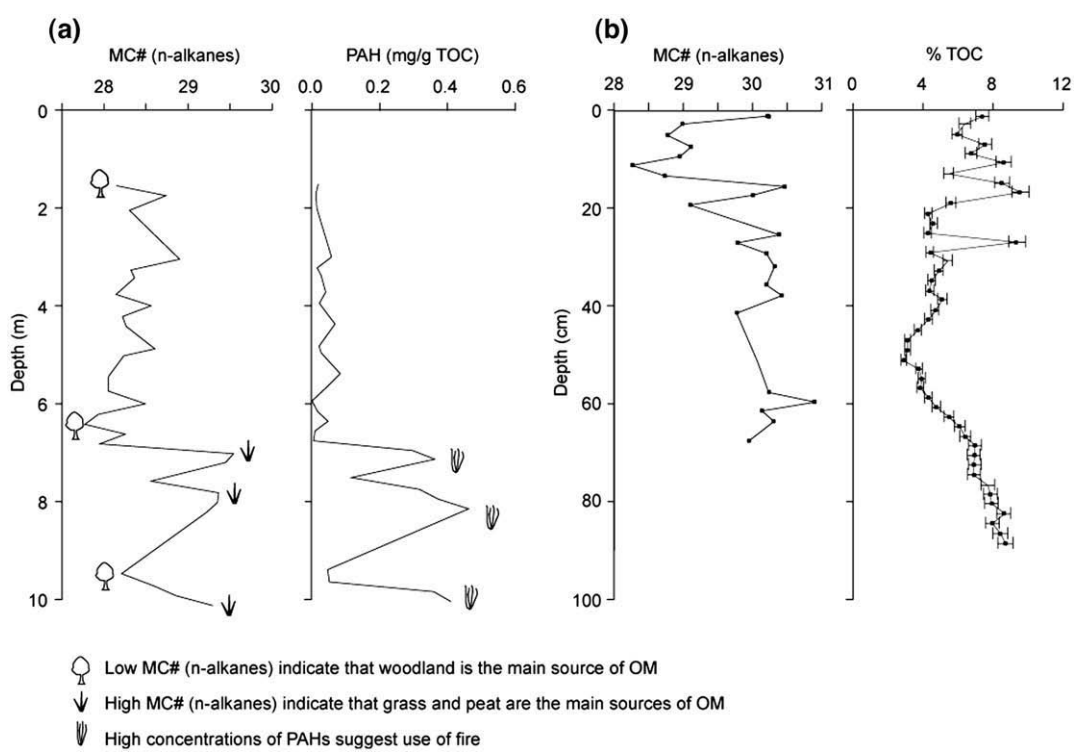

Fig. 11. Down-core profiles of Mean Carbon Number (MC#) of the *n*-alkanes and polycyclic aromatic hydrocarbons (PAHs) from Raydale Giddings Core A. Low values of MC# *n*-alkanes suggest a high contribution of organic matter (OM) from woodlands, whereas high values suggest that peat and grass are the main sources of OM to the sediment. High concentrations of PAHs suggest the use of fire in the catchment. + add in short core MC *n*-alkanes and TOC%.

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balance between allochthonous and autochthonous biomarkers points to a period of reduced erosion during the early to mid Holocene some time after the first spread of broad-leaved deciduous woodland into the region, but before the arrival of alder, ca. 7000 BP. There are still strong signs of the use of fire during this period.

In the next zone (2.5–7 m) (Fig. 11a), spanning at least part of the mid- to late Holocene, the biomarkers are, once more, predominantly terrestrially derived. There is a gradual increase in the MC# of the *n* alkanes (from 28 to 28.5) suggesting that there was a slow transition from woodland-derived to peat- and grassland-derived OM. PAHs were not detected in these sediments. The allochthonous organic input from these depths mostly postdates the earliest period of blanket peat development. The upper levels may represent the beginnings of blanket peat erosion.

The uppermost samples (0–2.5 m), from an undated period during the late Holocene have the lowest C/N ratios (~12) and contain the highest concentrations of both allochthonous and autochthonous biomarkers. The autochthonous biomarkers are comprised of both algal and bacterial indicators. This suggests the sediments derive from a period when the lake was more productive and that this coincided with a major influx of land-derived OM to the sediments.

The analysis of biomarkers from the Semer Water late Holocene minicore T3 (Fig. 11b) indicates that these sediments also are characterised by predominantly allochthonous OM. This is demonstrated by high (~25) C/N ratios and high relative concentrations of high molecular weight (HMW) fatty acids, ω–hydroxy acids, C_{29} sterols, and HMW *n*-alkanes. There is evidence of a minor contribution from autochthonous OM in the upper sediments (0–9 cm). This is indicated by the higher relative proportions of unsaturated acids. The source of these is difficult to assign as they may be due to algal or bacterial inputs. The MC# of the *n*-alkanes ranges from ~29 in the upper sediments (0–12 cm) to ~30 in the lower part of the core. This suggests that the dominant allochthonous input of OM in recent times has been from peat and grassland areas.

6.3. Granulometry, organic carbon and carbonate content

Particle size measurements recorded for the Semer Water sediments are from a single, central core. Sand content ranges from 16% to over 40%, clay content from 27% to 13%. Loss on ignition (LOI) determinations at 440 °C for another core hardly vary between 13 and 16%, whereas TOC % values in Core T3 are much more varied (Fig. 11b), ranging from 2 to 10%. In Core SL 1, they lie between 9 and 14%. Carbonate content in the lake sediment cores, whether estimated from LOI at 950 °C or based on HCl digestion, rarely exceeds 3%.

Granulometric measurements on Giddings Core A from Raydale (Fig. 7) show clay content mainly varying between 20 and 40%, with the highest values between 1.8 and 6.4 m depth. Within this depth range, sand content mostly varies between 10 and 30%. Above and below these depths, sand content is mostly between 40 and 50%. Granulometric measurements were also carried out on samples from between 2 m and 6 m from Raydale Core C (Fig. 7). These show the clay content declining from almost 20% at the base, to around 5% between 2 m and 3 m. Sand content increases from some 40% at the base of the core to around 80% above 3 m. The medium/coarse sand fraction suddenly increases at 3.8 m from negligible values to highly variable values mostly around 15–20%. The radiocarbon dates suggest that coarsening of sediments between 3.8 and 3 m took place soon after 3500 BP.

Comparison between granulometric and magnetic analyses in the Raydale Cores, as well as the magnetic measurements on particle size fractions obtained in earlier work on a core from the centre of Semer Water, confirm that high ARM values are linked to the clay fraction. This is typical of situations where bacterial magnetosomes contribute to the assemblage of magnetic minerals (Yu and Oldfield, 1993). It lends further support to the view that they overprint the detrital signature in many of the cores considered here.

Analyses of organic carbon and carbonate content in Raydale sediments are from Core A. From the base of the core to 7 m depth, organic carbon content is mostly below 3%. At this depth it increases to between 3 and 5%, with the occasional sample over 9% between 3 and 4 m. At some depth between 2 and 2.8 m, values increase to between 16 and 22%. Carbonate content is very variable, but mostly higher than in the Semer Water cores. Peak values in excess of 30% occur around 9.4 m and between 5.9 and 2.8 m. They fall within the depth range also characterized by high clay content.

7. Discussion

Limited chronological control, discontinuities in sedimentation and the lack of any clear means to link the existing data obtained from the Semer Water and Raydale cores exclude any possibility of developing a continuous story of sedimentation from the results presented here. Instead, we focus on five time intervals.

7.1. The early to mid-Holocene

This period is contained within Giddings Core A below c. 5.65 m (Fig. 10). There are no pollen records of vegetation cover during the period represented by the basal 1.5 m of sediment but from 9.1 m upwards, the pollen indicates an extensively forested landscape. The organic geochemistry record indicates that allochthonous plant material came from both wooded and non-wooded areas at various times during the period up to the Alnus rise. It is during this period that the relatively high values of PAHs point to the frequent and sustained occurrence of fire in the region. This part of the record falls within the period of Mesolithic occupation of the summit areas of the Pennines. The geochemical record thus provides an entirely independent record, additional to that derived from sub-peat charcoal, for the importance of fire during this period. A number of studies (Jacobi et al., 1976; Simmons, 1996; Innes and Simmons, 2000; Innes and Blackford, 2003) show that fire played a role in the Mesolithic woodland history in northern England, and have suggested that fire was part of woodland management strategy to increase animal concentration in the post-fire disturbed areas. The Pennines have yielded ample flint artefact evidence of Mesolithic age (Walker, 1956; Bartley et al., 1990), and are likely to have sustained a population engaged in hunting and forest disturbance activities similar to those identified elsewhere. However, anthropogenic causes are not the only explanation for fires in Mesolithic woodlands (Bradshaw et al., 1996; Brown, 1997; Tipping and Milburn, 2000), with drier climatic conditions providing a more permissive context for natural fires. Surface wetness data from peat bogs across northern England (Hughes et al., 2000; Charman et al., 2006) suggest that Mesolithic times, before 8500–8200 cal. BP were comparatively dry. Palaeo-data (e.g. charcoal and organic biomarkers) can provide evidence for the occurrence and magnitude of fire, however discerning the cause is a more difficult objective (Tipping and Milburn, 2000).

7.2. The mid-Holocene forest maximum

This period is preserved in Giddings Core A from c. 6.65 m to a poorly defined depth above 3 m. Both the pollen-analytical and organic geochemical data indicate at least a partially forested landscape with broad-leaved deciduous woodland. Fine-grained sediment predominated and the magnetic properties have much higher ARM values than do the catchment samples (Figs. 8 and 9). A significant contribution to the ARM values in the finest sediment fractions comes from the magnetosomes formed by magnetotactic bacteria. These are predominantly stable single domain in size and make a disproportionately high contribution to ARM measurements.

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Oldfield et al. (2003) showed that such magnetic assemblages are associated with minimum allochthonous particulate input. The combined magnetic and granulometric record from this part of Core A thus points to a period of landscape stability and limited clastic input via the main inflowing river. This is also the period of maximum carbonate concentration in Core A. A stable landscape with a significant solute input from the limestone slopes along the western side of the catchment is indicated.

Land-use change, climate and storms are regarded as the main triggers for phases of increased fluvial geomorphic activity (Harvey et al., 1981; Macklin, 1999; Lewin et al., 2005; Chiverrell et al., 2007). Storms often are the trigger for gully incision, but the radiocarbon dating of upland alluvial fans across northwest England shows that episodes of gully incision are concentrated in the late Holocene and have been attributed to localised responses to land-use change during the late Holocene (Harvey et al., 1981; Harvey, 1996; Chiverrell et al., 2007). The geomorphic evidence in Bardale relating to the early to mid-Holocene is somewhat ambiguous, with no comprehensive geochronological control. However, a period of relative geomorphic stability as interpreted from the palaeolimnological data during early to mid-Holocene times is in keeping with investigations of other nearby upland river systems (Harvey et al., 1981; Harvey and Renwick, 1987; Chiverrell et al., 2007).

7.3. The period from c. 4100 to 3500 cal. BP

Ascribing dates to the interval spanned by the sediments between 4 m and 9 m in Core C rests on assumptions about the validity of several of the ^{14}C dates from that core, and it is possible that the time interval represented is somewhat younger in age. A partially deforested landscape is indicated by the pollen record. Pollen data from sites in Wensleydale identify major clearances dated to the Bronze Age c. 4440–4160 cal. BP (Honeyman, 1985), and lowlands around Airedale to 4080–3730 cal. BP (Bartley et al., 1990). The whole of the dated interval just precedes the sharp increase in the coarse sand fraction at 3.8 m noted above. Nevertheless all the signs from the magnetic measurements (Figs. 8 and 9) are that the sediment is catchment-derived and, bearing in mind also the high sedimentation rate recorded, close to 1 cm per year, this represents a period of quite severe erosion. Similar magnetic properties characterize the upper, undated part of the core. There is tentative geomorphic evidence for erosion and aggradation during the late Holocene within Bardale, the onset of which has not been constrained other than it pre-dates 1690 1420 cal. BP. If as elsewhere in the uplands of northern England, the inception of tributary gullies systems has been linked with anthropogenic woodland clearance and destabilisation of the hillslopes (Harvey, 1996; Chiverrell et al., 2007), then it is a plausible hypothesis here but it requires further testing.

7.4. The period from c. 2000 to 100 cal. BP

The geochronological control for the geomorphic evidence in Bardale can at present only be regarded as tentative, nevertheless much of the evidence relates to the last 2000 years. Radiocarbon dating of buried mineral soils can secure a chronology for late Holocene landforms (Matthews, 1993; Harvey, 1996), however due caution is required in case the soils have been truncated by erosion or received younger organic matter from overlying soils. By analysing humic acids the radiocarbon dating targets the youngest organic fraction within buried soils (Matthews, 1993; Harvey, 1996), but does not preclude the possibility of residence time in the accumulation of organic matter. Nevertheless, the overlying deposits and younger landforms postdate the age determinations produced for each buried soil horizon. Laterally extensive buried soils between the accumulation of alluvial gravel units reflect that the Cow Stand Gill alluvial fan went through a phase of stability that ended after 1690–1420 cal. BP, and elsewhere within Bardale similar stability episodes ended after 930–770 cal. BP in the case of the main river terrace. The subsequent incision phase and further gravel aggradation associated with the deposits of the third river terrace is constrained to after 930–770 cal. BP. In summary the sequence can be interpreted as reflecting increased geomorphic activity during the late Holocene.

The lacustrine evidence for this period is somewhat limited at present, but cores from the centre of Semer Water show that rapid accumulation of sandy sediments have occurred through at least the last 500 years. The alluvial delta that comprises the valley floor of Raydale will include a substantial body of sediment that aggraded at this time. Supporting geomorphic evidence for heightened geomorphic instability during the late Holocene is available from the Swale/Ure confluence at Myton-on-Swale (Taylor et al., 2000), where boreholes show considerable accumulation (6 m) of fine-grained alluvial sediment during the period after 930–730 cal. BP. The record discerned for other nearby upland areas, the Forest of Bowland (Harvey and Renwick, 1987; Chiverrell et al., 2007) and the Howgill Fells (Harvey, 1996; Chiverrell et al., 2007), contains extensive evidence for heightened geomorphic activity and hillslope instability after dates that span the period 1400–800 cal. BP and this coincides with evidence for population expansion and increased upland land usage during Anglo-Norse and later times (Winchester, 1987; Chiverrell et al., 2007). Pollen data for this time period are not available for Semer Water, and more widely well-dated palaeoecological evidence is not abundant across the region. Sites in Nidderdale identify further substantial woodland clearances dated to c.1060 805 cal. BP (Tinsley, 1975), and in lowlands around Ribblesdale the first substantial woodland clearances took place 1515–1290 cal. BP (Bartley et al., 1990). Tinsley (1975) suggests that many of the upper tributary valleys and probably the steeper slopes retained woodland cover until these clearances. This apparent coincidence between the palaeoecological evidence for anthropogenically induced vegetation change, and both limnological and geomorphic evidence for landscape instability with the catchment of Semer Water can only be regarded as tentative at present.

7.5. The 20th century

The record for this time interval is disjointed and comes entirely from the Semer Water cores. Some cores at least experienced sedimentation rates during the second half of the century that were comparable to those dating from 4000–3000 cal. BP in Giddings Core C. The magnetic record shows clear signs both of a high detrital input and some bacterial overprinting, varying with depth. The organic geochemistry indicates that the sediments are characterised by predominantly allochthonous biomarkers. There is a minor contribution from autochthonous OM in the surficial sediments demonstrated by lower C/N ratios and higher proportions of unsaturated acids. This suggests that enhanced lake productivity may have occurred in recent times. However, as the first appearance of the autochthonous biomarkers coincides with the hiatus in the core, it is difficult to determine a timescale for this.

8. Conclusions

Deposition in the Raydale/Semer Water system is a complex mixture of alluvial, deltaic and fine-grained lacustrine material, with strong temporal and spatial variations in particle size, organic carbon and carbonate content. Comparison of the time intervals spanned by each set of cores shows that deposition has been at least partially progradational during the Holocene. Thus, although all the evidence suggests that fluvial incision and gully erosion of glacial diamict is likely to have been the dominant sediment source during the Holocene, attempts to refine this from the sediment record for specific time intervals on a quantitative basis will be difficult.

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Radiocarbon measurements based on terrestrial macrofossils and wood from the only dated Raydale core point to rapid sedimentation c. 4200–3200 cal. BP (of the order of 1 cm yr^{-1}) as well as to the incorporation of 'old' macroscopic material pre-dating the time of sediment accumulation. Improving chronological control will require, wherever possible, discrimination between terrestrial material contemporary with sedimentation and that derived from the erosion of stable organic residues in catchment soils and blanket peat. The Semer Water system provides a context within which to explore the onset and history of the erosion of Pennine summit blanket peat, but this will require unambiguous recognition of eroded peat whether through microscopic analysis or improved biomarker 'fingerprinting'. The combined indications from ^{210}Pb, ^{137}Cs and ^{14}C measurements carried out on the Semer Water cores point to discontinuities in recent sedimentation, although the magnetic susceptibility traces indicate that there are areas of conformable sedimentation within the lake. ^{137}Cs and ^{14}C data from the Semer Water Cores show that the depth range of post-1950 sediments varies from c.15 cm to >60 cm. The only demonstrably pre-modern ^{14}C date from the Semer Water cores points to the accumulation of some 2 m of sediment during the last 550 years in one of the central cores.

Although in many cores, the magnetic properties show overprinting of catchment 'signatures' by bacterial magnetosomes, the magnetic properties of a significant proportion of the Raydale sediments, from Core C in particular, correspond well with those of catchment-derived material. In this case, any *in situ* production of bacterial magnetite has been swamped by the volume of allochthonous material deposited. Biomarker data suggest that the dominant source of organic material in both the lake and Raydale sediment sequences is terrestrial. The only likely exception is the most recent (post-1950) Semer Water sediment, probably as a consequence of recent eutrophication. Early to mid-Holocene biomarkers indicate at least a partially wooded landscape as the dominant source of allochthonous organic matter. Stronger evidence for organic material derived from grassland and/or peat sources appears later in the sequence (as well as in the earliest part, pre-dating pollen records of mixed deciduous and pine woodland). The peaks in PAH present in the pre-*Alnus* rise Raydale sediment record provide evidence for the importance of fire in the region during the Mesolithic.

The evidence for catchment instability during the last 2000 years is not fully matched by any of the lacustrine sequences studied so far. The Raydale cores sampled and dated, whether by radiocarbon or more crudely by pollen counts, are mostly too old, and the oldest material dated from Semer Water itself is only 550 years old. However, the bulk of the Raydale infill lies between the present southern limits of the lake and the Raydale cores analysed. Moreover, gouge cores have already proved sediment depths in excess of 16–18 m in parts of this fill. Clearly, it is to this part of the system that attention must turn in future in order to link the geomorphic and palaeolimnological records more closely. Developing secure quantitative estimates of total sedimentation for key episodes during the Holocene will depend on comprehensive coring of both the Raydale and sub-aquatic sediments at least to the Late Devensian/Holocene contact. Given the complex interdigitation of limnic, prograding deltaic and fluvial sediments in Raydale, this will require not only multiple cores, but extensive chronological control. Successful coring of the currently sub-aquatic sediments calls for raft-based equipment capable of penetrating and retrieving cores from extremely cohesive material. Finally, success in bringing the history of sedimentation up to the present day will require a series of cores spanning the last two centuries without any significant hiatus. This has proved difficult so far, despite multiple magnetic profiles and detailed radioisotope measurements.

One of the key outcomes of this account is a demonstration of the potential of the site for further work linking geomorphological and palaeolimnological studies within the same lake-catchment framework. Organic biogeochemistry can identify the key linkages, since the results relate to the nature and provenance of organic material in the sediment, not simply to the general nature of catchment vegetation, as is the case with pollen analysis. More research is likely to reveal important pointers both from the changing relative proportions of different allochthonous OM biomarkers and from their relative richness or paucity as a whole. For example, where the sediment is impoverished in biomarkers, despite strong indications of erosion from other lines of evidence, one likely inference would be that the sediments were largely derived, as in this study, from channel bank and gully erosion rather than erosion of surface soil. Such evidence complements that provided by magnetic measurements on the minerogenic sediments (cf. Oldfield et al., 2003). At the same time, these preliminary results force acknowledgement of the formidable challenges posed by such a complex site if any attempt is made to unite the geomorphic and palaeolimnological evidence into a coherent and continuous, quantified account of erosion, sediment yields and sources, and Holocene denudational processes.

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