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Suspended sediment characterization and tracing using a magnetic fingerprinting technique: Bassenthwaite Lake, Cumbria, UK

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Abstract: Robust identification of catchment suspended sediment sources is a prerequisite both for understanding sediment delivery processes and targeting of effective mitigation measures. Fine sediment delivery can pose universal management problems, especially with regard to nutrient run-off and lake siltation. Here, 19 suspended sediment samplers were located within the three main tributary inflows to Lake Bassenthwaite, a key but vulnerable site of special scientific interest, with water quality problems linked to accelerated delivery of fine sediment. Magnetic properties of contemporary suspended sediments, collected on a monthly basis, were measured on a particle size-specific basis and compared with the lake sediment core-tops. Ferrimagnetic grain size and magnetic 'hardness' vary significantly between the suspended sediments collected from the different tributaries, with the 8–31 μm and 31–63 μm clastic grain fractions displaying greatest magnetic contrasts. Post-depositional formation of bacterial magnetosomes is evident in the 2–8 μm and < 2 μm fractions of the lake sediments. Thus, for comparison with the potential source suspended sediments, we use only the detrital, clastic fractions, 8–31 μm and 31–63 μm. The lake sediment magnetic properties show little spatial variation, indicating through-lake transport of sediment (no evidence was found of postdepositional diagenetic sulphide formation). Magnetic comparisons between the potential sources and the lake surface sediments indicate that Newlands Beck, providing only ~ 10% of the lake's hydraulic load, is the main contributor of sediment to the deep basin of the lake. Sediments from the River Derwent subcatchment, contributing ~ 80% of the hydraulic load, are possibly stored either on the floodplain or in shallower areas of the lake.

Key words: Environmental magnetism, sediment sourcing, suspended sediment, mineral magntics, magnetic susceptibility, magnetic fingerprinting, lake sediments, English Lake District, Bassenthwaite Lake.

Introduction

Accelerated sediment delivery to streams can incur numerous downstream impacts, including degradation of water quality and damaging subsequent deposition of sediment in low-energy environments. Soil erosion, water quality and lake and/or reservoir sedimentation are increasing problems in many areas internationally. In fluvial systems, fine suspended sediment is an important vector of nutrients, especially phosphorus, and heavy metals and organic contaminants. Fine sediment is itself increasingly recognized as a pollutant in its own right, when delivered at accelerated rates (eg, Foster and Charlesworth, 1996; Walling *et al*., 1997; Meharg *et al*., 1999). In the temperate, mid-latitude context, suspended sediment load constitutes the dominant mode of particulate material loss from catchments. Its transport is flood-driven and highly episodic, with ~ 90% of the annual suspended load being transported within ~ 10% of the time, concentrated in the winter months (eg, Thompson and Oldfield, 1986; Walling and Webb, 1987; Russell *et al*., 1998). Such 'pulsing' of sediment supply in the temporal sense may further be matched spatially. In the very large regional catchment of the Burdekin River (NE Queensland), for example, suspended sediment sources may be mobilized by localized cyclonic and erosive events, such that large proportions of sediment export are generated from very small proportions of the catchment (Prosser *et al*., 2002; Maher *et al*., unpublished data, 2007) Identification of fine suspended sediment sources is a prerequisite both for understanding fluvial geomorphic process and systems (eg, Collins and Walling, 2004) and for designing strategies to reduce sediment transport, delivery and yields (eg, Russell *et al*., 2001). Upland management practices can significantly

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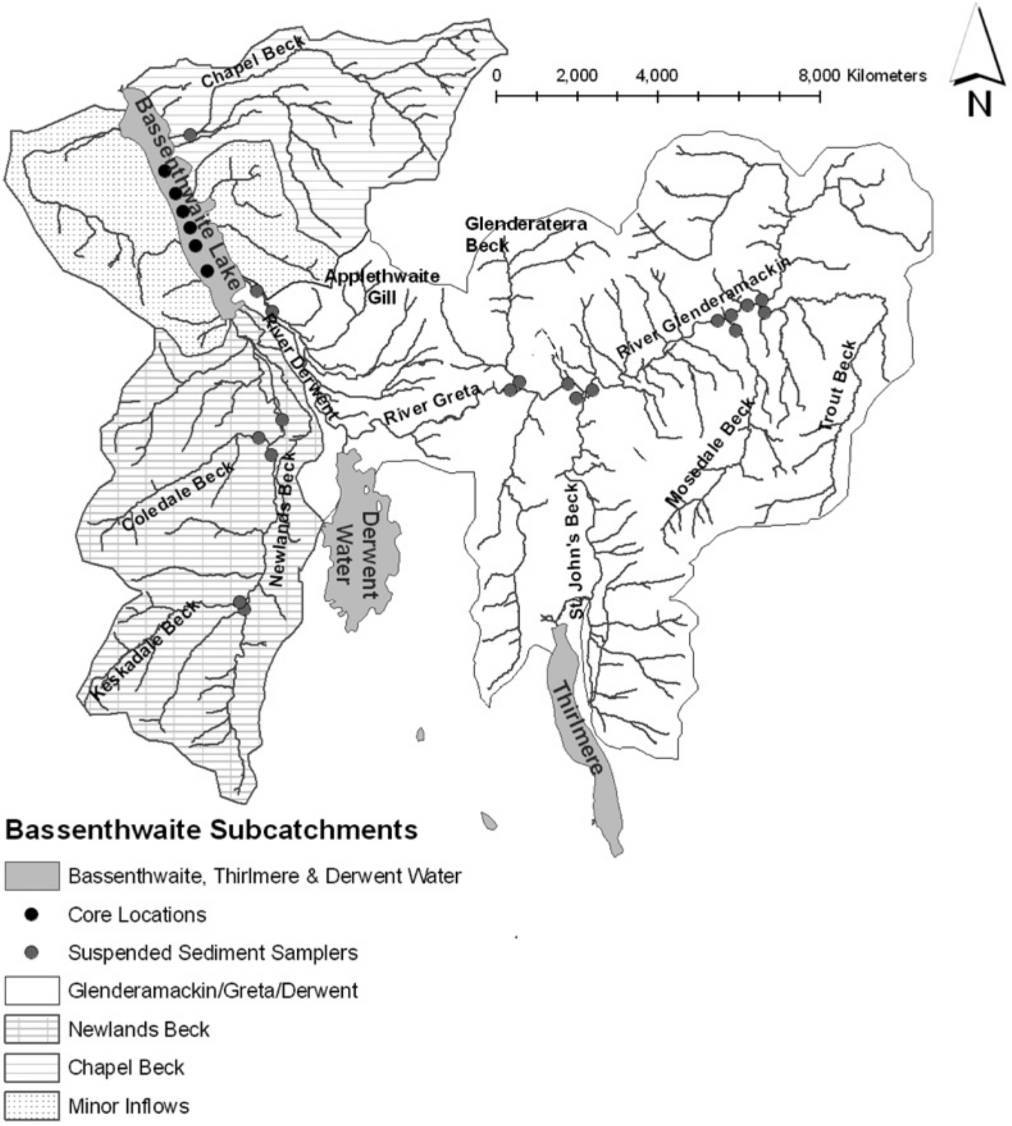


Figure 1 Map of the Bassenthwaite Catchment, with the River Greta to the east and Newlands Beck to the southwest

influence run-off and river regimes, with consequences for sediment detachment, transport and delivery. In the UK, for example, post-war agricultural policy and EU-led economic incentives have led particularly to increased sheep stocking densities in the uplands, associated with grassland expansion, pasture improvement and drainage (eg, Orr and Carling, 2006). Hydrological changes arising from changed upland management practices may be further intensified through the observed increase in the frequency and magnitude of UK rainfall events, through enhanced influx of westerly weather systems (eg, Wilby *et al*., 1997).

Bassenthwaite Lake, in the English Lake District, is currently subjected to problems thought to be associated with increased fine sediment delivery (Orr *et al*., 2004; Winfield *et al*., 2004). The lake, designated a Site of Special Scientific Interest (SSSI), supports one of only two UK populations of vendace (*Coregonus albula*); however, its numbers are in decline, thought to result partly from deposition of fine sediment in spawning gravels and an increase in trophic status (Winfield *et al*., 2004). An estimated 74% of the lake's annual phosphorus load is reported to emanate from diffuse (particulate-borne) rather than point sources (Bennion *et al*., 2000). Direct methods of sediment fingerprinting hold most potential for robust identification of catchment suspended sediment sources. Sediment fingerprinting using the magnetic properties of soils and sediments has previously been exploited to characterize catchment subareas on a variety of spatial scales, from tens to thousands of square kilometres (eg, Caitcheon, 1993, 1998), and to identify sediment sources in a range of different climates and topographies (Walling *et al*., 1979; Oldfield et al., 1985; Thompson and Oldfield, 1986; Yu and Oldfield, 1993). Sediment magnetic properties can be notably particle size-dependent (eg, Dearing *et al*., 1985; Oldfield *et al*., 1985; Maher, 1986). Similarly, magnetic changes down-core in lake sediments can reflect changes in particle size of the accumulating sediment (eg, Stober and Thompson, 1979).

Here, we build upon Frank Oldfield's far-sighted development of magnetic tools for tracing human impacts on Holocene environmental systems, and report the results of magnetic characterization of contemporary suspended sediment inflows from the Bassenthwaite catchment. We compare these with the present-day lake sediment properties, on a particle size-specific basis, in order to identify the major sources of suspended sediment at the present day. Such source identification is of key importance in targeting mitigation measures aimed at minimizing sediment and nutrient export from the surrounding catchment.

Site description

The catchment of Bassenthwaite Lake (54:39:13N, 3:13:00W) includes Derwent Water and Thirlmere (Figure 1); as these two water bodies effectively act as 'upstream' sediment traps for transported material, the potential sediment source area for Lake Bassenthwaite is effectively restricted to 240 km^2. There are three main inflows to the lake. The River Derwent, which provides ~ 80% of the lake's hydraulic load (Hilton *et al.*, 1993), drains the largest, eastern, area of the catchment (Figure 1). Newlands Beck, providing ~ 10% of the hydraulic load, drains a significantly smaller area in the southwest of the catchment, and Chapel Beck drains a major portion of the northern part of the catchment. The catchment geology is dominated by the Skiddaw Slate Group (metamorphosed Ordovician, marine turbiditic and hemi-pelagic greywacke, arenite, siltstone and mudstones (British Geological Survey (BGS), 1992)), with small areas of the Borrowdale Volcanic Group, a dominantly extrusive volcanic association, in the southwest of the catchment (BGS, 1992). Catchment topography varies greatly, from the +900 m peaks of Helvellyn and Skiddaw to the outflow of Bassenthwaite at 71 m. Land use is predominantly pastoral farming, mostly concentrated in the upper Derwent subcatchment where open fells, valley floors and moorland dominate, compared with the steep more 'mountainous' areas present in the Newlands subcatchment. These subcatchment geomorphological characteristics are reflected in their hydrographs (Figure 2). With the same rainfall event recorded at three stations, the Newlands flood response is flashier (peak discharges sooner in the event, steeper recessional limbs) than the upper Derwent catchment. The Portinscale station illustrates the damping effect of Derwent Water on the flood regime, with shallow recessional limbs demonstrating this lake's contribution after peak discharge. In a recent geomorphological assessment (Orr *et al.*, 2004), 20–25 % of the catchment soils were considered as having 'high' erosion risk; these areas are almost entirely located on the high fells with overgrazing and human trampling considered the main erosive agents.

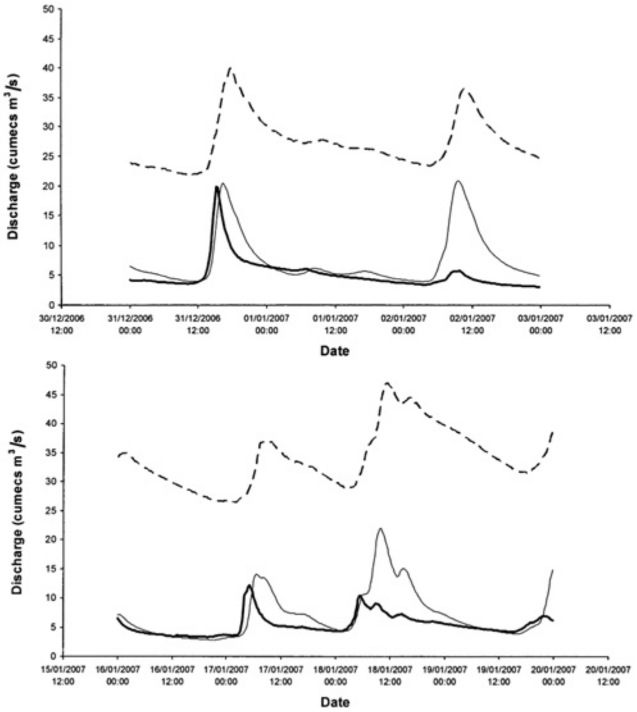


Figure 2 Two examples of flood hydrographs for three stations in the Bassenthwaite catchment, draining the: Newlands subcatchment (thin black line); Glenderamackin (upper Derwent) subcatchment (thick black line) and the Derwent at Portinscale, downstream of the confluence with Derwent Water (dashed black line)

Methodology

Suspended sediment sampling and sediment coring

Time-integrated suspended sediment samplers (Philips *et al.*, 2000) were installed throughout the catchment at 19 selected locations (Figure 1), with site selection based on hydraulic load, subcatchment characteristics and erosion potential (Orr *et al.*, 2004). The samplers integrate variations in suspended sediment over a monthly collection period, producing a composite sample (~ 10 g), large enough to allow detailed magnetic and geochemical analyses. Suspended sediment may be composed of a heterogeneous, aggregate mix of particle sizes (eg, Slattery and Burt, 1997). Although the sampler preferentially retains sand and silt-sized material (Philips *et al.*, 2000), clay fractions are also sampled because of their aggregation (thus, they deposit more readily than would be predicted for single particles in Stoke's Law). Figure 1 also shows the location of a southeast (inflow) to northwest (outflow) transect of six 1-m cores obtained from the lake, in July 2004, using a mini-Mackereth corer.

Sample preparation

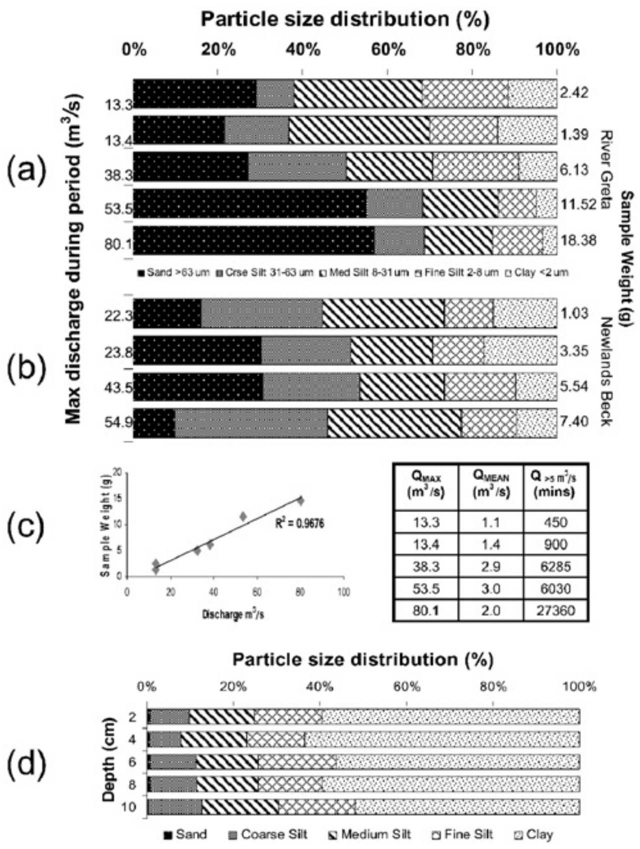
In the laboratory, suspended sediments were recovered by settling from 10 l collection vessels, and the lake sediment cores were sliced into 1–2 cm samples. As the properties (including the magnetic properties) of sediments are often strongly particle-size dependent (eg, Wall and Wilding, 1976; Oldfield *et al.*, 1985; Collins *et al.*, 1997), the suspended sediments were separated into five particle size fractions prior to analysis. Samples were treated with 25 ml 10% Calgon solution and placed in an ultrasonic bath to enhance particle dispersal. They were wet sieved at 63 μm and the < 63 μm material separated by settling in Atterberg columns into the following size fractions: clay (< 2 μm), fine silt (2–8 μm), medium silt (8–31 μm) and coarse silt (31–63 μm). The separated fractions were dried at 40°C, before being packed into 10 cc plastic sample pots and immobilized prior to magnetic analyses.

Magnetic measurements

Measured magnetic parameters included low frequency magnetic susceptibility, susceptibility of anhysteretic remanent magnetization (χ_{arm}) and stepwise acquisition of isothermal remanent magnetization (IRM). Magnetic susceptibility was measured at 0.47 kHz on a Bartington MS2B susceptibility sensor. χ_{arm} was imparted using a Molspin demagnetizer with ARM attachment at 80 mT, in a 0.08 mT DC biasing field and then stepwise demagnetized (in AC fields of 5, 10, 15, 20, 30, 40 and 80 mT). IRM was acquired (in DC fields of 20, 40, 50, 100, 200 and 300 mT) using a Molspin pulse magnetizer and at 1 T (regarded as the saturation IRM (SIRM)) using a Newport electromagnet. Samples were demagnetized in the same steps as for χ_{arm}, with an additional ac demagnetisation step of 100mT. All remanence measurements were made on a Molspin Minispin *(*noise level 2.5 10^{-5} A/m*)* and all measurements are expressed on a mass-normalized basis. From these measurements, concentration-independent, interparametric ratios were also calculated. All magnetic measurements were made at the Centre for Environmental Magnetism and Palaeomagnetism (CEMP) at Lancaster University.

X-ray fluorescence

X-ray fluorescence (XRF) analyses were undertaken to identify the major and minor elemental concentrations of a subset (12) of the suspended sediments and core-top samples. Major and minor elemental components were determined on high dilution fused sample beads (0.1 g ignited sample to 3 g flux, lithium tetraborate) using a PANalytical Axios Advanced x-ray fluorescence spectrometer, at the Department of Geology, Leicester University. The fusion bead analysis, including determination of the loss on ignition (LOI, sample ignited at 1050°C for 1 h and weight loss recorded), provides a normal lower limit of detection (LLD) of 0.01% with precision better than 0.5% at 100 × the LLD.



Q_{MAX} (m^3/s)	Q_{MEAN} (m^3/s)	$Q_{>5\ m^3/s}$ (mins)
13.3	1.1	450
13.4	1.4	900
38.3	2.9	6285
53.5	3.0	6030
80.1	2.0	27360

Figure 3 Particle size distribution of suspended sediments, for (a) the River Greta and (b) Newlands Beck, with relation to (c) discharge parameters from the River Greta. Core-top particle size distribution for core 3 is also shown (d)

Statistical analysis, fuzzy clustering

Statistical analysis was undertaken on the measured magnetic and elemental signatures of the suspended sediments and the lake core-top sediments. First, *t*-tests were used to identify which magnetic parameters afforded most discrimination between suspended sediment sources. Second, fuzzy clustering was used to classify the magnetic and selected elemental properties of the sources and sediments. Unlike hierarchal and k-means cluster analysis, fuzzy clustering does not force a sample to belong to a particular cluster; instead it assigns the sample an affinity to each cluster from 0 (no similarity) to 1 (identical). The FuzME program of Minasny and McBratney (2002) was used to first classify the suspended sediments into clusters, with a second run used to match the core-top sediments against these defined sources. The data (representing 77 samples) were checked to ensure they displayed a normal distribution; outliers were identified (> 3 × standard deviation from the mean) and removed (1 data point), to avoid undue influence on the cluster results (Hanesch *et al.*, 2001).

Results and discussion

Suspended sediments

For suspended sediment samples, strong significant correlation exists between suspended sediment mass and the maximum recorded discharge ($R^2 = 0.97$, $n = 6$, significance level of >99.9% for the Derwent and $R^2 = 0.89$ for Newlands Beck). Over six collection periods, higher rainfall and river discharge resulted in both increased amounts and proportions of sand-sized (> 63 μm) material (Figure 3). These data suggest that as discharge varies, so does the mass, composition, and possibly the source, of the resulting suspended sediment.

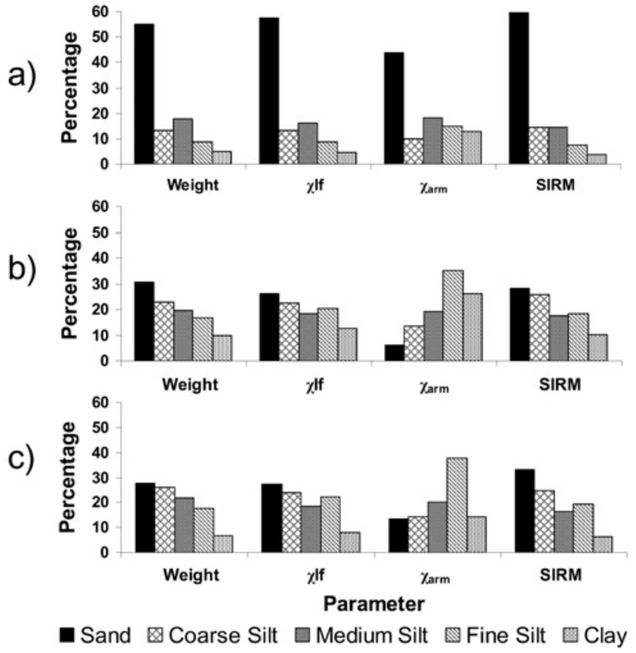


Figure 4 Particle size distribution and the percentage contributions of each size fraction to the bulk suspended sediment sample for three magnetic parameters, (a) Glenderamackin/Greta/Derwent; (b) Newlands Beck; (c) Chapel Beck. Based on suspended sediment collections (a) 20 March 2005–21 April 2005 and (b) and (c); 20 December 2005–27 January 2006

Magnetic properties of suspended sediments

The suspended sediment samples collected from the Bassenthwaite inflows have magnetic susceptibility values ranging from ~ 0.012–0.3 10^{-6} m^3/kg. All of the suspended sediment samples are dominated by a strongly magnetic (ferrimagnetic) signal with ~ 90% of their SIRM acquired in applied fields below 300 mT. Different detrital fractions can be important in carrying the magnetic signal depending upon geology and soil type (eg, Maher, 1986, 1998). Figure 4 illustrates the strong particle size-dependence of the suspended sediment magnetic properties from the main Bassenthwaite inflows. Both the particle size distribution and magnetic properties of the Glenderamackin/Greta/Derwent samples are dominated by the sand fraction. In Newlands Beck and Chapel Beck, magnetic susceptibility and SIRM are preferentially carried by the sand fractions. In contrast χ_{arm} is dominantly contributed by the finer fractions (< 2 μm and 2–8 μm), regardless that these two fractions contribute least to the mass of the bulk sample. These data emphasize the need for magnetic characterization of sediments and sources on a particle size-specific basis. As magnetic concentration can vary with discharge, ratio data (eg, $IRM_{20\ mT}$/SIRM, $IRM_{1T-100\ mT}$/SIRM and χ_{arm}/SIRM) were used to identify contrasts in sample magnetic mineralogy and magnetic grain size. Comparison of the ferrimagnetically dominated suspended sediments with sized magnetites (Figure 5) indicates the presence of magnetically single domain-like material in the clay fractions and much coarser, magnetically multidomain-like material in the coarser clastic size fractions.

Spatial magnetic variation of suspended sediments

Sand-sized material (> 63 μm) was omitted from the magnetic analyses, as in the majority of cases too little material was recovered from the samplers for accurate measurement. Table 1 shows the results of unpaired *t*-tests on four tributary groupings (Glenderamackin/Greta/Derwent, Newlands Beck, Chapel Beck and the moorland tributaries, Mosedale and Troutbeck) of the four

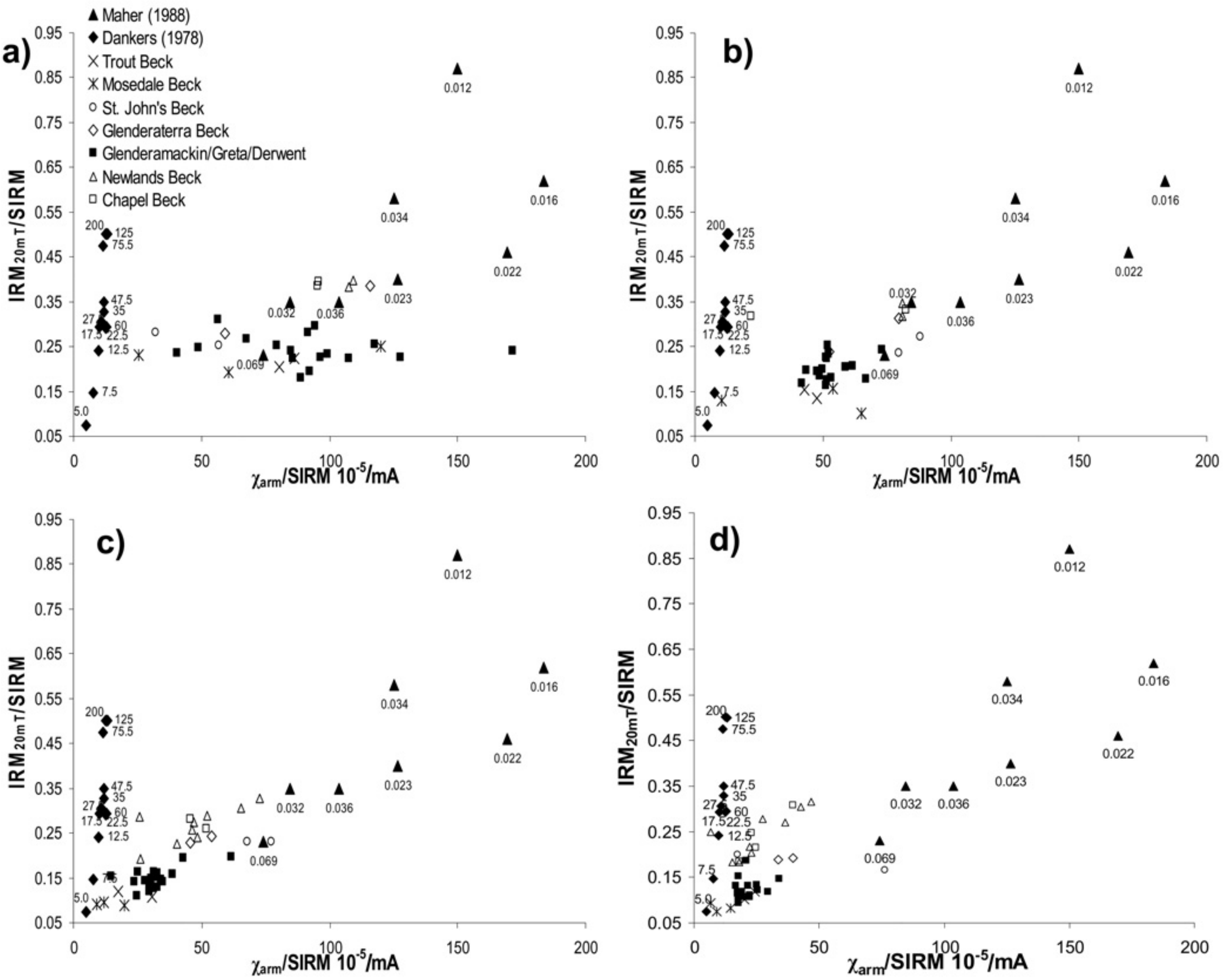


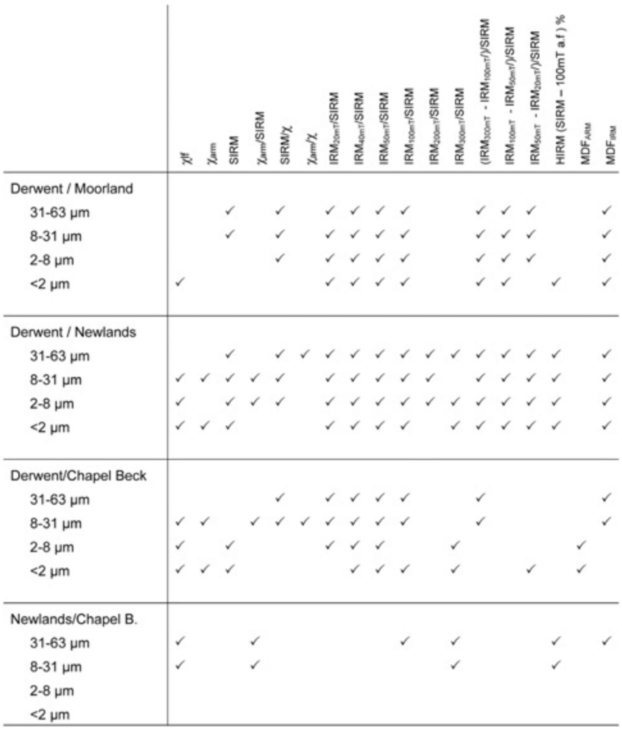
Figure 5 Comparison of χarm/SIRM and IRM^{20mT}/SIRM for the suspended sediment samples and sized synthetic magnetites from Maher (1988) and Dankers (1978). Particle size fractions: (a) < 2 µm; (b) 2–8 µm; (c) 8–31 µm; (d) 31–63 µm and numbers indicate magnetite grain size

remaining size fractions. Statistically significant variation in the magnetic properties of the suspended sediment groupings exists within the catchment. Unpaired *t*-tests reveal this variation to be highest between (a) the Derwent system and (b) the Newlands and Chapel Beck systems. Although magnetically similar in many respects, the Chapel Beck and Newlands Beck suspended sediments can be differentiated using magnetic hardness parameters. The silt fractions, 8–31 µm and 31–63 µm, appear most useful for subcatchment discrimination with SIRM, χ_{arm}/SIRM, SIRM/χ, IRM$_{20mT}$/SIRM, IRM$_{40mT}$/SIRM, IRM$_{50mT}$/SIRM, IRM$_{100mT}$/SIRM and MDF$_{IRM}$ often providing statistically robust means for discrimination between suspended sediment sources. Figure 6 summarizes some of these observed magnetic contrasts. For the 8–31 µm and 31–63 µm data especially, three main groupings of suspended sediment samples are evident: in the diagram, the middle group of samples is derived exclusively from the Derwent river system, incorporating the Greta and Glenderamackin (solid symbols); those to the lower right (cross symbols) are from Mosedale Beck and Troutbeck (tributaries of the Glenderamackin); and those to the upper left (open symbols) are mainly from the Newlands and Chapel Beck river systems. Although these data represent samples collected over several different hydraulic periods, it is notable that the between-tributary variation is greater than the within-tributary variation, especially for Newlands and Chapel Beck, and the Mosedale Beck and Troutbeck samples. Conversely, the overlap observed between samples from within the Greta/Glenderamackin system is unsurprising given that they are all from different reaches within the same subcatchment. Further information on the magnetic contrasts between the major inflows is summarized in Table 2. It is notable that compared with Chapel Beck, Newlands Beck appears magnetically ‘softer’, thus providing a means of discrimination between these two potential sources. In summary, it seems a combination of different magnetic parameters can be used both to characterize and discriminate between the suspended sediments carried by the three major inflows to Bassenthwaite Lake.

Lake sediment cores

Six 1-m cores were taken along a southeast–northwest transect along the deepest part of the Bassenthwaite Lake basin. Prior to any particle size separation, magnetic susceptibility was measured on the bulk samples whilst wet, and subsequently re-measured upon drying of the sediments. No significant changes in susceptibility were observed, suggesting the absence of any unstable magnetic sulphides, such as greigite, which have been reported in some freshwater sediment sequences (eg, Snowball and Thompson, 1988; Hilton, 1990; Roberts 1995). As with the suspended sediments, the lake sediments were then split into the same five particle size fractions, through dispersion, wet sieving and timed settling. The particle size distribution for Core 3, from 10

Table 1 t-test results showing magnetic parameters significant at a level of 0.05 for four different suspended sediment groupings



	χlf	χ_{arm}	SIRM	χ_{arm}/SIRM	SIRM/χ	χ_{arm}/χ	IRM_{20mT}/SIRM	IRM_{40mT}/SIRM	IRM_{50mT}/SIRM	IRM_{100mT}/SIRM	IRM_{200mT}/SIRM	IRM_{300mT}/SIRM	$(IRM_{300mT} - IRM_{100mT})$/SIRM	$(IRM_{100mT} - IRM_{50mT})$/SIRM	$(IRM_{50mT} - IRM_{20mT})$/SIRM	HIRM (SIRM – 100mT a.f.) %	MDF_{ARM}	MDF_{IRM}
Derwent / Moorland																		
31-63 μm			✓		✓		✓	✓	✓	✓			✓	✓	✓			✓
8-31 μm			✓		✓		✓	✓	✓	✓			✓	✓	✓			✓
2-8 μm					✓		✓	✓	✓	✓			✓	✓	✓			✓
<2 μm	✓						✓	✓	✓	✓			✓	✓		✓		✓
Derwent / Newlands																		
31-63 μm			✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
8-31 μm	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓	✓		✓
2-8 μm	✓		✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
<2 μm	✓	✓	✓				✓	✓	✓	✓		✓	✓	✓	✓	✓		✓
Derwent/Chapel Beck																		
31-63 μm					✓		✓	✓	✓	✓			✓					✓
8-31 μm	✓	✓		✓	✓	✓	✓	✓	✓	✓			✓					✓
2-8 μm	✓		✓				✓	✓	✓			✓					✓	
<2 μm	✓	✓	✓					✓	✓	✓		✓			✓		✓	
Newlands/Chapel B.																		
31-63 μm	✓			✓						✓		✓				✓		✓
8-31 μm	✓			✓								✓				✓		
2-8 μm																		
<2 μm																		

cm depth to the sediment/water interface (Figure 3d), shows the distribution is dominated by clay-sized particles with the >8 μm fractions contributing ~ 23–30% of the bulk sample. It is thought that the silt fractions are responsible for clogging the vendace spawning gravels (Winfield *et al*., 2004). Magnetic measurements were undertaken on the sized fractions, which, like the suspended sediments, also display strong particle size-dependence of their magnetic properties. In all six core-tops, the lake sediments appear dominated by relatively soft ferrimagnetic material. The high values of χ_{arm}/SIRM (eg, > 1.5 10^3 mA^{-1}) and χ_{arm}/χ (eg, 10–30) recorded in the 2–8 μm and <2 μm fractions are indicative of the presence of bacterial magnetosomes (Oldfield, 1999). Magnetotactic bacteria are common in natural systems (eg, Blakemore, 1975; Hesse and Stolz, 1999), typically producing intracellular chains of ferrimagnetic minerals, of predominantly single domain (SD) magnetic grain size. Thus, the 2–8 μm and < 2 μm Bassenthwaite lake sediment fractions may be magnetically dominated by postdepositional, *in situ* bacterial formation of ferrimagnets and thus are unsuitable for allogenic, detrital sediment tracing. Hence the coarser fractions (> 8 μm), which appear to contain no autochthonous magnetic component, are the most appropriate clastic grain size range for sediment source discrimination in the Bassenthwaite catchment.

Comparison between the cores may provide spatial information about sedimentation rates, sediment sources and any sediment (re)distribution through the lake. In contrast with the range of magnetic variations shown by the different sets of suspended sediments, the core-top sediments show little difference in their magnetic properties (Figure 7), only Cores 1 and 6 displaying slightly different magnetic signatures. Located at the southern and northern extremes of the transect, respectively, these two cores may have greater exposure to local source influences. Overall, however, recent sediment deposited in the lake has a fairly uniform magnetic signature, possibly reflecting efficient sediment distribution through the lake towards its northwestern outflow. On this basis, Chapel Beck might be discounted as a major sediment source to the lake; its northerly location would preclude significant sediment redistribution against the general southeast to northwest flow of the lake.

Discussion

Suspended sediment magnetic properties

The 8–31 μm and 31–63 μm samples from the Newlands catchment are the 'softest' magnetically and have lowest values of

Table 2 Means and standard deviations of nine selected magnetic properties and Pb and Zr concentrations for the 31–63 μm particle size fraction

	G'mackin/ Greta/Derwent		Newlands Beck		Chapel Beck		Cores 1–6	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
χlf (10^{-6} m^3/g)	0.27	0.05	0.28	0.02	0.25	0.00	0.28	0.05
χ_{arm} (10^{-6} Am^2/g)	1.05	0.58	0.52	0.19	0.54	0.13	0.74	0.16
SIRM (10^{-5} Am^2/g)	3691	383	2417	202	2128	223	3368	394
χ_{arm}/SIRM (10^{-5}m/A)	27.9	12.5	23.4	11.0	26.2	9.3	23.6	6.45
IRM_{100mT}/SIRM	0.60	0.07	0.77	0.03	0.74	0.01	0.74	0.03
$(IRM_{50mT}–IRM_{20mT})$/SIRM	0.17	0.11	0.31	0.02	0.28	0.02	0.29	0.02
SIRM–a.f.$_{100mT}$ (%)	8.79	0.60	6.03	1.09	9.27	0.43	6.19	1.03
MDF_{ARM} (mT)	17.7	2.5	16.9	3.4	14.9	2.5	Samples often too small	
MDF_{IRM} (mT)	21.70	3.60	12.90	0.73	14.30	0.45	12.68	1.13
Pb (μg/g)			204.3	UN*				
	59.9	5.7	630.7	CB*	46.8	4.1	167.6	31.2
			348.1	LN*				
Zr (μg/g)			275.2	UN*				
	321.2	11.6	238.8	CB*	299.7	16.1	240.3	21.0
			267.7	LN*				

Average taken from five collections of suspended sediment and six lake cores. Newlands Beck has the highest concentrations of Pb and lowest concentrations of Zr and is the softest magnetically, with high values of IRM_{100mT}/SIRM and $(IRM_{50mT}–IRM_{20mT})$/SIRM and low values of the demagnetization parameters SIRM–A.F.$_{100mT}$ and MDF_{IRM}, relative to Chapel Beck and the magnetically 'hard' Glenderamckin/Greta/Derwent system. CB* is Coledale Beck, a tributary of Newlands Beck, UN* is (Upper) Newlands Beck before its confluence with CB and LN is (Lower) Newlands Beck, downstream of its confluence with CB.

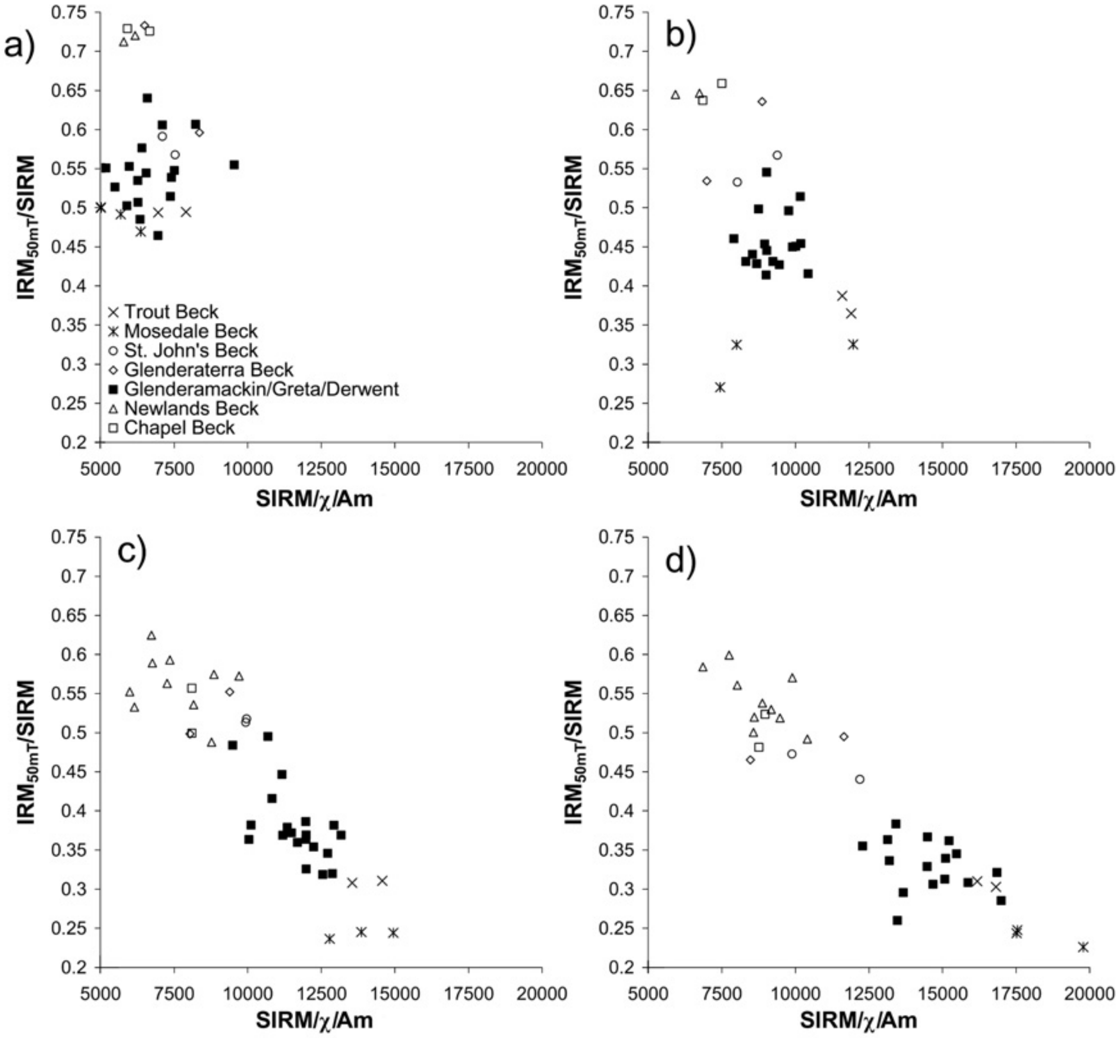


Figure 6 Comparison of SIRM/χ and $IRM_{50mT}/SIRM$ for the Bassenthwaite catchment suspended sediment samples. Particle size fractions: (a) < 2 µm; (b) 2–8 µm; (c) 8–31 µm; (d) 31–63 µm

SIRM/χ (< 10 k/Am). The upper Newlands subcatchment, dominated by steep, craggy slopes associated with the Borrowdale Volcanic Group, and with extensive relict and active gullying of glacial and paraglacial diamicts (Chiverrell *et al*., 2007), is classified as having high erosion risk potential and has the greatest concentration of bare ground in the Bassenthwaite catchment (Orr *et al*., 2004). Examination of suspended sediment samples through the 6 km Newlands Beck system reveals little change in their magnetic properties, suggesting that a similar, consistent source of sediment from the upper subcatchment is efficiently transported through the system. Further, engineering structures occur in the lower reaches of Newlands Beck to prevent floodplain inundation, by promoting higher discharge and reducing in-channel and floodplain storage. In contrast, the 8–31 µm and 31–63 µm particle size fractions of the Derwent suspended samples are magnetically ‘harder’ than the Newlands samples, and have higher values of SIRM/χ. Topography and land use in the Derwent/Greta/Glenderamackin system is more heterogeneous (possibly reflected in the greater scatter in Figures 6 and 7) with areas of bare ground on steep craggy fells but also flat valley bottoms given over to pasture. The magnetic signatures of the Derwent system, whilst distinctive, appear as an intermediary variant within the whole Bassenthwaite catchment, with the Newlands system at one extreme and Mosedale Beck and Trout Beck at the other. Mosedale, Trout, Glenderaterra and St Johns Becks are all tributaries of the Derwent/Greta/Glenderamackin system. Although the magnetic properties of their suspended sediments differ from those of the main channel, they appear rapidly ‘buffered’ downstream, maintaining a fairly constant, apparently well-mixed, suspended sediment signature. However, it is interesting to note the local influences possibly affecting the magnetic signatures of these individual subcatchments. High moorland (~ 200–600 m) areas dominated by peat on the Threlkeld and Matterdale commons appear associated with magnetically weak suspended sediments with a ‘hard’ remanence component (Trout and Mosedale Beck sediments, Figure 6), possibly reflecting pedogenic dissolution even of detrital ferrites (Maher, 1986; Maher and Taylor, 1988). The Glenderaterra Beck subcatchment similarly comprises a mix of bare crags and steep valley sides, whereas St Johns Beck drains a low-altitude area dominated by pasture, possibly causally linked to some *in situ*, pedogenic formation of ‘soft’ ferrimagnets, with magnetically single domain/superparamagnetic grain sizes (Figure 5). Chapel Beck drains both significant areas of bare ground (located around the high point of Skiddaw) and, in its lower reaches, improved pasture, with little channel engineering. These varied subcatchment characteristics develop the signature summarized in Figure 7 and Table 2, with magnetic behaviour ‘softer’ than the Derwent system sediments but ‘harder’ than those from Newlands Beck and with slightly higher SIRM/χ values.

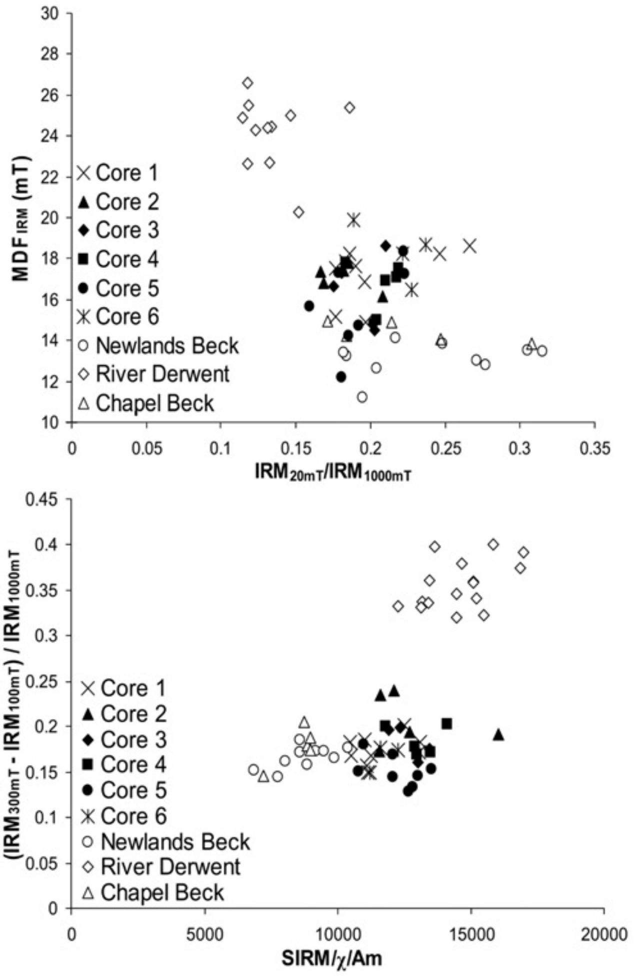


Figure 7 Magnetic ratio data for cores 1–6 and for suspended sediments from Newlands Beck, the River Derwent and Chapel Beck. All data from the 31–63 μm particle size fraction

Lake sediment magnetic properties

The > 8 μm fractions, unaffected by any postdepositional, authigenic magnetic change, appear the most suitable for characterization of the allochthonous lake sediment components. Table 2 shows the mean (and standard deviation) magnetic data for the 31–63 μm fraction of the cores. The major characteristic of the core-top sediments is their relatively magnetically soft nature, illustrated by ease of acquisition and loss of IRM in relatively low fields; 18–21% of IRM is acquired at a field of ~ 20 mT and $\mathrm{MDF}_{\mathrm{IRM}}$ ranges from 11 to 14 mT. SIRM/χ values are relatively low, as are those for the granulometry parameters sensitive to fine/ultrafine magnetic grains, χ_{arm}/SIRM and χ_{arm}/χ. These data suggest the core-top samples are dominated by coarse-grained, multidomain-like, ferrimagnetic minerals.

Sediment tracing

Magnetic measurements appear to differentiate between the three major potential suspended sediment inputs to Bassenthwaite. Sediment source identification should therefore be possible from particle size-specific comparisons of the core-top sediment signatures with those of the suspended sediments. A range of magnetic properties indicate the dissimilarity of the Derwent subcatchment suspended sediments compared with the core-tops (eg, Figure 7 and Table 2), in contrast to the Newlands and Chapel Beck signatures, which match much more closely the lake sediment properties. Remanence acquisition curves provide further discrimination potential (Figure 8). The six core-tops show both very little variability and a characteristically 'softer' pattern of magnetic remanence acquisition (Figure 8). Contemporary suspended sediments from the Glenderamackin/Greta/Derwent are magnetically harder than the recent lake sediments, acquiring and losing their remanence at much higher fields (Figure 8). The remanence acquisition behaviour of the Chapel Beck suspended sediments is much closer to the lake sediments but slightly magnetically harder. Conversely, the Newlands Beck suspended sediments match very closely the remanence behaviour of the core-tops. Newlands Beck, located at the far southwestern end of the lake, thus appears to be the key source of the suspended sediment delivered to the deep lake bed at the present day. Within this subcatchment, there is a variety of potential sources of the sediment. The valley bottoms are pastorally farmed, with extensive soil poaching, relict and active gully sites exist in the upper catchment (Chiverrell, 2006) and there is a history of mining in the Newlands catchment, with significant works at Force Crag, Goldscope and Thornthwaite mines (Postlethwaite, 1913). Further work can be undertaken to identify which of these within-subcatchment sources is most significant at present (R.G. Hatfield and B.A. Maher, unpublished data, 2007).

Elemental analysis by XRF of a subset of suspended and core-top sediments identifies key differences between the suspended sediments, notably in their Pb and Zr concentrations (Table 2). Pb concentrations are highest in Coledale Beck suspended sediments, with slightly lower values in Newlands Beck (upstream of its confluence with Coledale Beck) and minimum values in the Derwent and Chapel Beck systems. Conversely, Zr values are highest in the Derwent and Chapel Beck inflows and lowest in Newlands Beck.

Quantitative source ascription

Thus far, sources have been ascribed on a qualitative basis; iterative modelling and multivariate analysis tools (eg, fuzzy clustering) enable a more quantitative approach to sediment sourcing. On the basis of our magnetic data, it can first be assumed there are three key possible sources: Newlands Beck, the River Derwent and the <2 μm fraction from the lake sediments. The latter is included to identify any contamination by bacterial magnetosomes through inefficient removal of fines during particle size separation. Iterative theoretical mixing of sources generate the data envelopes shown in Figure 9. These envelopes illustrate ranges of modelled values obtained by theoretical mixing of the 'Derwent' and 'bacterial magnetite' source components with the 'Newlands Beck' sediment magnetic properties. Most of the core-top samples lie within the 100% Newlands Beck envelope; a few samples plot towards the Derwent source indicating at most ~ 20% contribution from the Derwent. Any Derwent contribution greater than this results in a modelled range of values significantly different from the core-top data points (Figure 9).

Statistical analysis of the suspended sediments and the core-top magnetic and selected elemental properties by fuzzy clustering (eg, Hanesch *et al.*, 2001) indicates that the potential sources can be differentiated into five statistically separate clusters (Figure 10). *t*-tests show that $\mathrm{IRM}_{20\mathrm{mT}}$/SIRM, SIRM–$\mathrm{IRM}_{100\mathrm{mT}}$ a.f. demagnetization and $\mathrm{MDF}_{\mathrm{IRM}}$ discriminate well between the sediment sources (Table 1). In addition to these parameters, χ_{arm}/SIRM is included in the clustering, as this magnetic grain size parameter characterizes the < 2 μm fraction well. Also included in the clustering, as independent parameters, are sediment Pb and Zr concentrations, which are distinctive between the different subcatchments (Table 2). Bacterial magnetite-dominated sediments form their own unique cluster, cluster 5 (C5), whilst C1 is unique to the Derwent/Greta system. The XRF data (especially Pb concentrations) help discriminate between different tributaries in the Newlands subcatchment. C4 represents Coledale Beck, an area with significant metalliferous mining activity in the past, whilst clusters 3 and 2 characterize Newlands Beck before (C3) and after (C2) its confluence with Coledale Beck. When the core-top sediment properties are matched against these

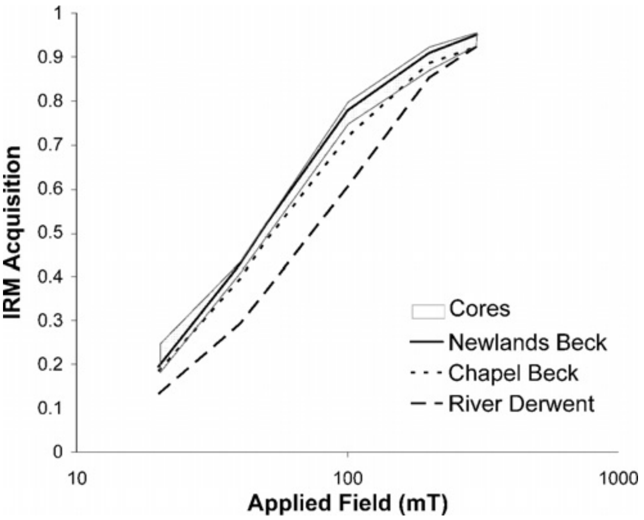


Figure 8 IRM acquisition curves for cores 1–6 (shaded area), and for suspended sediments from Newlands Beck, the River Derwent and Chapel Beck. All data from the 31–63 μm particle size fraction

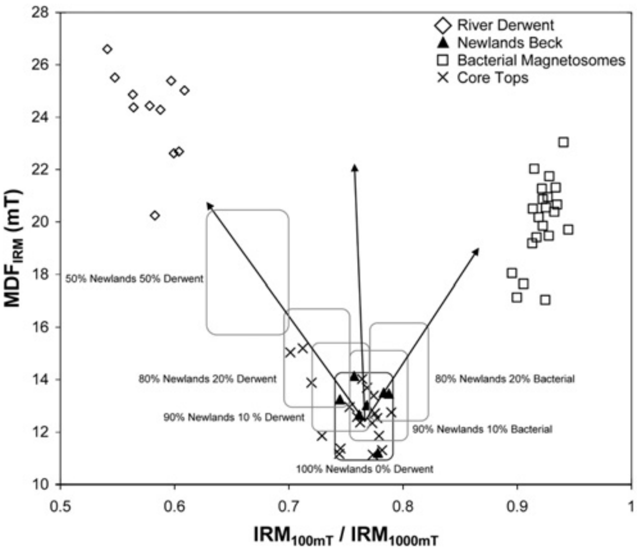


Figure 9 Results of iterative mixing of representative samples (31–63 μm) from the Derwent, Newlands Beck and the bacterial magnetite-dominated (< 2 μm) lake sediment fraction, compared with the core-top sediments

source clusters, they show close to 100% affinity with the 'upstream' Newlands Beck sample cluster, C3 (Figure 10). Thus, the recent sediment within the lake can be confidently and quantitatively ascribed to Newlands Beck, and particularly to its upper segment (ie, upstream of its confluence with Coledale Beck).

Lake sediment/catchment linkages

Newlands Beck contributes only ~ 10% of the hydraulic load to Bassenthwaite, in contrast to the Derwent, which contributes as much as 80% (Hilton *et al*., 1993). During storm events, the River Derwent often records suspended sediment loads in excess of 2.2 mg/l (Hall *et al*., 2001). Given the magnetic evidence here, however, this sediment appears not to reach the deep basin of the lake, suggesting its storage on the floodplain of the Derwent and/or its channel and/or in shallower areas of the lake, with no subsequent movement into the deeper basin. The lower reaches of Newlands Beck are floored by cobbles and boulders, indicating two processes: lack of in-channel storage and high discharge rates. Postglacially, Derwent Water and Bassenthwaite were one lake (Smith, 2004); the Derwent and Newlands Beck have since created an intervening isthmus by deposition of sediment. Our magnetic data suggest that the Derwent continues to deposit much of its suspended sediment load at its floodplain and/or delta, whereas the channelized and flashy flows of Newlands Beck appear to be the major source of sediment delivery to the basin of Bassenthwaite Lake at the present day.

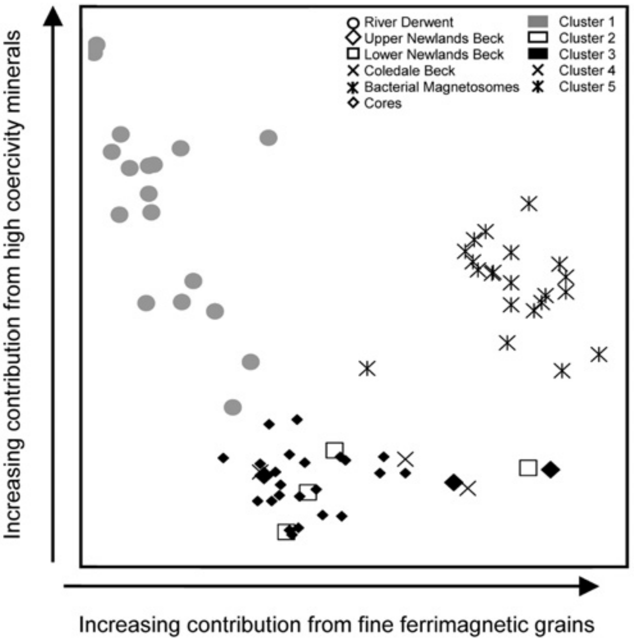


Figure 10 Results of the fuzzy clustering analysis showing differentiation between sources, and the dominant cluster affiliation of the core-top sediments with upper Newlands Beck. Symbols: shapes represent different sources, shading represents different clusters

Conclusions

(1) Magnetic properties appear to be a valuable tool to characterize and distinguish between the major suspended sediment inflows into an upland lake of key scientific interest, Lake Bassenthwaite, at the present day.

(2) The magnetic properties of the contemporary suspended sediments are strongly particle size-dependent. For sediment source tracing, coarser particle size fractions (8–31 μm and 31–63 μm) are the most reliable. The magnetic signatures of these size fractions are distinctive, conservative, and preclude any contribution by postdepositional, *in situ* formation of bacterial magnetite.

(3) Similar magnetic measurements on the core-top sediments from a transect of six 1-m lake sediment cores from Bassenthwaite, again on a particle size fraction-specific basis, allow comparison with the suspended sediment inflows. Suspended sediments transported from the Newlands Beck system appear to dominate the contemporary magnetic signature of the six Bassenthwaite cores, suggesting that this is the major source (>> 80%) of sediment to the deeper basin area of Bassenthwaite Lake.

(4) Catchment characteristics, channel state, engineering structures and sediment storage thus appear to be more important aspects and processes for sediment delivery than the hydraulic load of each river inflow. Whilst the River Derwent dominates the hydrological input to Bassenthwaite, much of its suspended load appears to be stored either in its channel and/or on the floodplain. Conversely, Newlands Beck appears to have been transformed

into a transport-dominated zone, with ultimate deposition of its suspended load on the bed of Bassenthwaite Lake.

(5) Magnetic fingerprinting provides a sensitive and quantitative basis for sediment source ascription in this upland temperate context. Independent corroboration of the magnetic signatures can be obtained by complementary elemental analysis of smaller subsets of magnetically targeted sources.

(6) The ability to identify fine sediment sources is increasingly critical in a range of different environments and contexts, to enable cost-effective targeting of mitigation measures in order to reduce the influx of material and its resultant effects on lake water quality and survival prospects for rare species.

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