JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 49, NO. 3, P. 0801–0812
FIGS. 1–9, SEPTEMBER, 1979

0022-4472/79/0049-0801/$03.00

38

MAGNETIC SUSCEPTIBILITY AND PARTICLE-SIZE DISTRIBUTION IN RECENT SEDIMENTS OF THE LOCH LOMOND DRAINAGE BASIN, SCOTLAND[1]

R. THOMPSON AND D. J. MORTON
Department of Geophysics, Edinburgh University
Edinburgh, EH9 3JZ, Scotland

ABSTRACT: Bedrock, till, soil, stream and beach samples have been analysed from the Loch Lomond drainage basin together with thirty sediment cores, either 6-m or 1-m long, from the lake itself. Magnetic analyses of susceptibility (χ) and isothermal remanence (IRM) have been made on dried bulk samples and various particle-size fractions. Down-core variations in susceptibility show a series of maxima and minima which correlate with horizons of finer-and coarser-particles respectively. Magnetic susceptibility can thus be used to establish a lithostratigraphy for the lake sediments. This stratigraphy can be linked to a time scale based on palaeomagnetic, isotopic and pollen analyses. The source of the magnetic minerals in the lake could be either primary iron oxides in the bedrock or till, or alternatively secondary iron oxides developed in the soils. The possibilities of either as the major source are discussed in terms of three proposed models: a source model, an erosional/transport model and a depositional model. Variable erosion of primary magnetite explains most of the down-core, between-core and within-drainage basin changes in mineral magnetic properties.

INTRODUCTION

The data presented here were obtained as part of a broader ongoing research project regarding the origin of magnetic minerals and natural remanence in recent sediments. Earlier studies in the United Kingdom and overseas (Thompson, 1973, 1976; Thompson et al., 1975; Oldfield, 1977; Oldfield et al., 1979) have demonstrated the following points. Initial susceptibility (χ) in the lake sediments of Lough Neagh, N. Ireland is most probably a function of the influx of detrital allochthonous material from the drainage basin as a result of erosion of substrate and possibly soils (Thompson et al., 1975). Variation of susceptibility and related magnetic properties with depth down a core provides a basis for between-core correlations within a particular lake, based on rapid 'whole core' measurements (Molyneux and Thompson, 1973; Thompson et al., 1975; Oldfield, 1977). This variation in susceptibility also corresponds to biostratigraphical divisions in some lake sediments (Thompson et al., 1975) so that variations are generally taken to represent synchronous events within that particular lake. Consequently, the down-core variations in susceptibility may permit the rapid recognition of stratigraphic changes not usually detectable by the naked eye in lake sediments and provide some insight into the sedimentation patterns within a lake.

The principal aim of the current study was to investigate any relationship that existed between the variations in magnetic susceptibility down a core and its lithology or particle-size. The particle-size of a sediment is one of its most easily measured and important properties. Any relationship between particle-size and susceptibility would suggest that down-core variations in susceptibility could be directly interpreted in terms of sedimentation within any particular lake and its drainage basin.

LOCATION AND METHODS

Sampling

The Loch Lomond drainage basin in western Scotland (Fig. 1) was chosen for this work because of its large size, the variation in local rock types and the existence of several separate river systems draining into the loch, each with different geological provenances. The lake is 7120 ha in area (the largest in Scotland), 36.4 km long, 190 m at its deepest with a mean depth of 37.2 m, and has a volume of 2.63×10^9 m^3. The

---

[1] Manuscript received October 30, 1978; revised March 13, 1979.

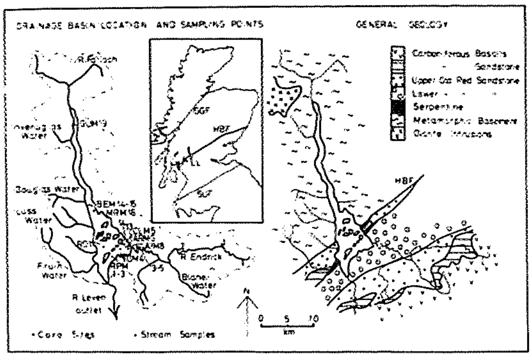

FIG. 1.—Location, general geology of Loch Lomond area and location of coring sites. Major Scottish faults:- Highland Boundary fault, HBF; Great Glen fault, GGF and Southern Uplands fault, SUF; and Loch Lomond LL are shown on the inset map.

drainage basin has 10 times the area of the lake.

Samples were analysed from the three distinct geological provenances that occur around the lake. Dalradian metamorphic rocks, mostly quartzite, schist and phyllite, along with some grits and intrusions, are exposed around much of the lake, north of the Highland Boundary Zone. South of this zone, a suite of Old Red Sandstone red clastic sedimentary rocks occurs around the southern shore, whereas farther to the south-east and west, thick sequences of Carboniferous basaltic rocks occur along the margins of the drainage basin. Small, 25-mm long, 25-mm diameter, cores of each of these rock-types were collected.

Numerous stream samples were taken from the rivers of the drainage basin and were treated in the laboratory prior to making magnetic measurements. The samples were taken from sand deposits on river bar-tails or deltas of the river mouths using a piece of plastic core tubing about 150 mm long. A small bulk sample of about 100 g was wet sieved from each sample and all material finer than −1 phi (2mm) in the sand, silt and clay fractions was collected. Large particles of organic material were removed by decantation and then the sample was treated with hydrogen peroxide, washed with distilled water, and finally dried slowly in an oven at 40° C.

An additional 200 g of sediment was taken from the original stream sample, and wet sieved for 30 minutes. Particle size fractions from −1 phi (2mm) to +5 phi (32 μm) plus the 'pan' fraction were collected and treated as above. The individual particle-size fractions were ultrasonically cleaned to remove as far as possible any fine particles of clay that were adhering to the coarser material, and consequently masking the magnetic properties of the separated detrital fractions. Chemical methods of cleaning the samples were avoided. The dried weight of sediments in each particle-size fraction was determined, and mean/median grain size and sorting coefficients were calculated for each bulk sample.

Both 6-m and 1-m cores were collected using pneumatic corers (Mackereth, 1958, 1969) at several localities (Fig. 2) during 1976 and 1977. The cores were 'logged' for lithological, textural, structural and color changes along their length. The 1-m cores were subsampled at 3.5 or 10 cm intervals after magnetic scanning. Dried bulk samples and individual particle-size fractions were obtained at each of the sub-sample intervals.

Magnetic Measurements

Magnetic susceptibility (χ), 'saturation' isothermal remanent magnetization (SIRM), and coercivity of isothermal remanence (B_{CR}) were measured on the bed-rock, till, soil, stream deposits and lake-bed cores. Magnetic susceptibility (or magnetizability) was measured using an air cored bridge in a low magnetic field at a frequency of 10 kHz (e.g., Molyneux and Thompson, 1973). The susceptibility of a natural material is mainly dependent on its iron oxide content which is dominated by the 'magnetite' component. 'Magnetite' has a specific susceptibility of about 5×10^{-4} m^3 kg^{-1}. SIRM was produced in a uniform 1-tesla field in a conventional electromagnet and measured in a fluxgate magnetometer (Molyneux 1971). Both χ and SIRM take about 10 seconds to measure. SIRM is also largely held by iron oxides in natural samples. The size and shape of the magnetic crystals, however, influence their remanence more than their susceptibility. The ratio of SIRM to susceptibility thus provides information about the types of magnetic crystals and their size (Table 1), whereas susceptibility alone relates

TABLE 1

	χ $10^{-6}m^3kg^{-1}$	SIRM $10^{-3}Am^2kg^{-1}$	SIRM/χ 10^3Am^{-1}	B_{CR} $10^{-3}T$
Coarse magnetite crystals 100 μm	500	1200	2.5	15
Fine magnetite crystals < 1 μm	500	12000	25	50
Fine haematite crystals	0.3	75	250	500
Dalradian mica schist	0.1	0.08	0.8	21
Dalradian quartzite	—	0.05	—	35
Gabbro	0.3	0.7	2	24
Devonian red sandstone	0.1	10	100	300
Carboniferous basic lavas	25	500	20	15
Carboniferous quartzite	—	0.25	—	35
Till on schist	2	7	3	29
Till on basic lavas	5.7	77	14	50
Till on red sandstone	0.2	4	24	176
Topsoil on schist	0.2	1.4	7	31
Topsoil on basalt till	3.3	52	16	50
Topsoil on sandstone till	0.3	5	16	68
R. Endrick headwaters sand	3.1	37	13	42
R. Endrick headwaters silt	10.0	70	7	37
R. Endrick mouth sand	0.44	5	12	35
R. Endrick mouth silt	2.0	15	8	42
R. Fruin sand	0.20	0.8	4	25
R. Fruin silt	1.2	15	12	30
R. Luss sand	0.8	8	10	28
R. Luss silt	0.4	1.5	4	30
R. Inveruglas sand	3.1	14	5	17
R. Inveruglas silt	5.0	14	3	16
R. Falloch sand	1.1	5	5	40
R. Falloch silt	1.3	8	6	30
Island beach sand	0.2	1	5	—
Island beach silt	0.8	5	7	—
Endrick delta coarse sand	0.25	2	8	—
Endrick delta fine sand	0.44	4	9	—
Endrick delta coarse silt	0.88	8	9	—
Endrick delta silt/clay	1.9	18	10	—
South basin deep water core	1.3	12	10	—
North basin deep water core	0.6	4.5	7	—

to the concentration of the magnetic crystals. B_{CR} (the reverse d.c. field required to reduce the SIRM to zero) was calculated from a series of ten IRM measurements.

The IRMs were produced at gradually increasing reverse field strength following the growth and measurement of the original SIRM. B_{CR} provides a rapid method of distinguishing between common natural magnetic minerals. Iron oxides of corundum structure, e.g., titanohematites, have remanent coercivities above 2 tesla. Crystals of spinel structure, e.g., magnetite or maghemite, have remanent coercivities below 50 mT. The B_{CR} of magnetite also decreases with increasing grain size (Table 1).

Magnetic scanning of the lake cores was carried out before they were subsampled for more detailed analyses. Magnetic susceptibility and natural horizontal remanence scanning was performed using the instruments of Molyneux and Thompson (1973) and Molyneux et al. (1972).

BETWEEN CORE CORRELATIONS

Preliminary measurements of relative declination (the horizontal component of natural magnetic remanence), intensity and magnetic susceptibility were made on the sediment while still in the core tube. It is possible from these measurements to see a very clear correlation between the 6-m cores collected, and to match unambiguously the 1-m cores to the 6-m cores (Fig. 2).

Variations of magnetic susceptibility with depth are often used to correlate between cores from the same lake where similar depositional histories are expected. This is the case for Loch Lomond (Fig. 2) where, particularly in the southern Loch Lomond cores, the susceptibility record has many

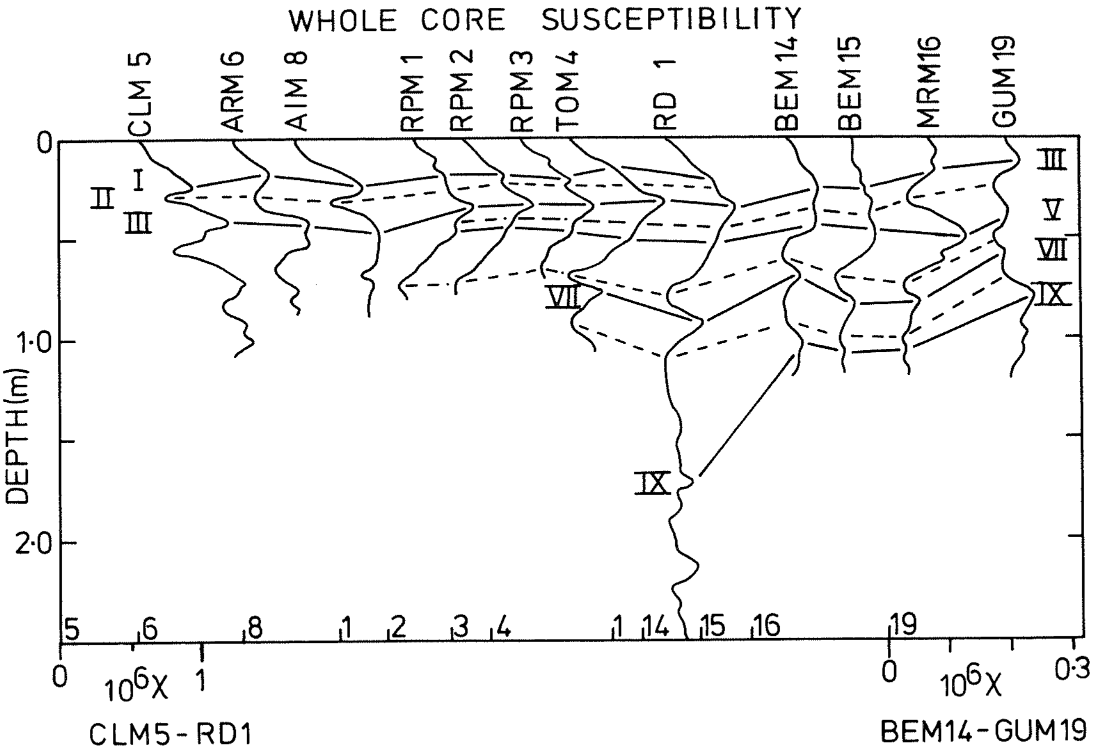

FIG. 2.—Whole core susceptibility correlations for Loch Lomond sediments. For location of cores, see Figure 1.

distinctive features that permit between-core correlations. Nine maxima and minima are visible in the top meter (Fig. 2 I–IX).

The declination records are clear and very consistent between cores, indicating their geomagnetic origin. The declination curves (Fig. 3) were compared with those of Mackereth (1971) from Lake Windermere, which have been dated radiometrically. The Loch Lomond cores, however, have an accumulation rate approaching twice that of the Lake Windermere cores (Dickson et al., 1978) and the uppermost sediments have a much lower water content. Consequently the record near the top of the core is much more clearly defined.

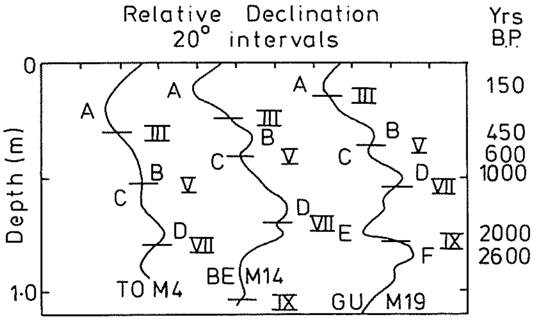

FIG. 3.—Relative declination profiles with 'magnetic' ages for three 1-m cores from Loch Lomond. Susceptibility maxima and minima (III–IX) from Figure 2. Declination turning points labelled as in Turner and Thompson (1979).

Logs of the declination (Fig. 3) and inclination were compared with London magnetic observatory records covering the past 250 years, and with archaeomagnetic inclination data extending back to 1700 B.P. A deposition curve has been drawn up on the basis of these 'palaeomagnetic' ages. This enables the declination swings (Fig. 3 A–F) and the susceptibility maxima and minima (Fig. 2 I–IX) to be correlated with a time scale (Fig. 3). The accumulation rate of the fine-grained core (Fig. 2 LLRDI) from 60 m depth at the southern end of Loch Lomond varies from 0.5 mm/yr at a depth of 3.5 m below

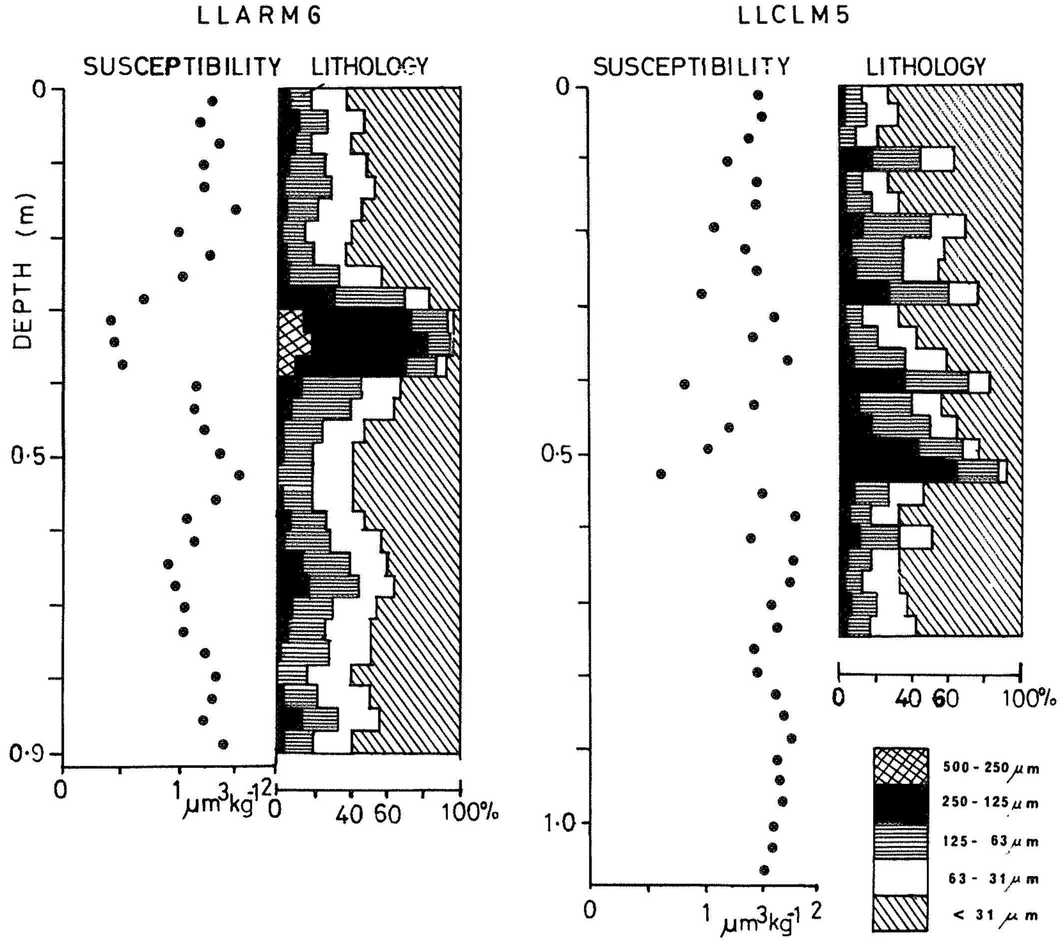

FIG. 4.—Variation of specific susceptibility with depth for two near shore 1-m cores from the Endrick delta, Loch Lomond. The change in particle-size composition of the sediment core is shown.

the sediment/water interface (which corresponds to ~5000 yr B.P.) to ~1.0 mm/yr in the top meter of sediment. This increase in accumulation rate is partly exaggerated by an increase in water content in the top 0.5 m of the core.

SUSCEPTIBILITY CORRELATIONS WITH GRAIN SIZE

Specific magnetic data from dried weight bulk sub-samples from two marginal and one deep water core are shown in Figures 4 and 5. It can be seen that there is a good correlation between the maxima and minima in the susceptibility and SIRM curves. This suggests that either property could be used to provide a correlation between cores within a lake. There is also a marked correlation between the particle size of the sediment and the maxima/minima peaks of susceptibility. The near shore cores (Fig. 4) from the Endrick delta top comprise a vertical alternation of horizons of coarse and fine particles arranged in coarsening upwards units that resemble the minor mouth bar-crevasse channel couplets described by Elliot (1977) from recent deltaic deposits. In both these cores low susceptibility values correspond to a high proportion of coarse sediment (sand), whereas high susceptibility values correspond to horizons of finer (silt) material. A similar but less pronounced pattern of susceptibility/particle-size correlation is seen in the deep-water core (Fig. 5) where low susceptibility values tend to correspond to coarser horizons. Pipette analyses of the

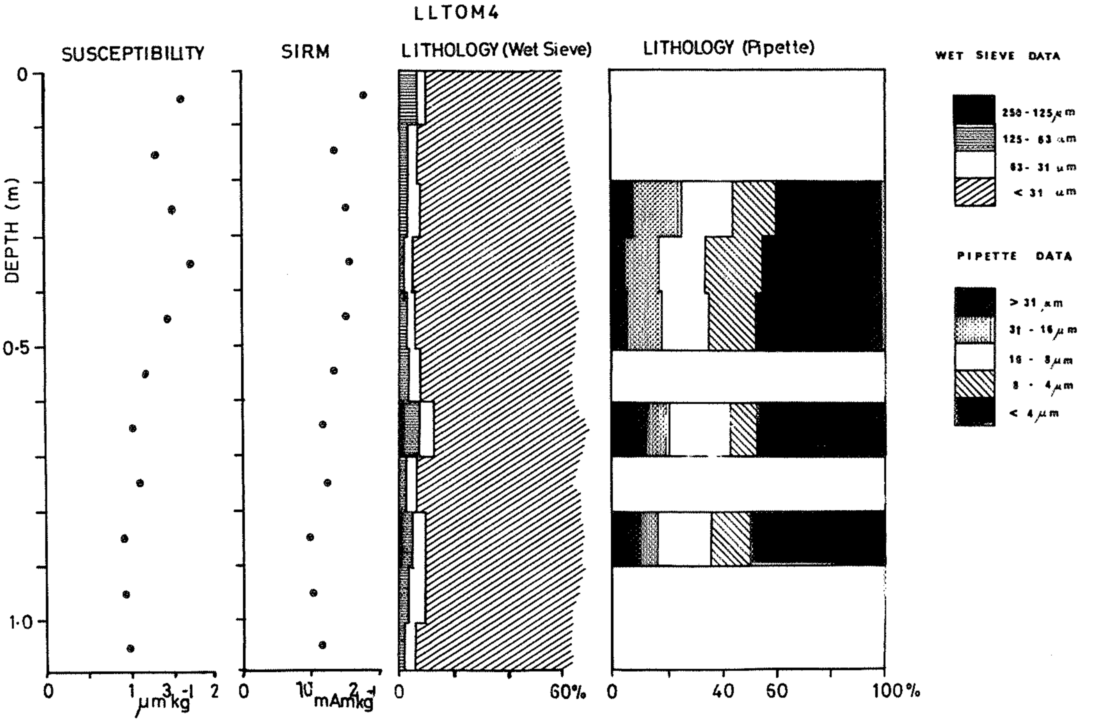

FIG. 5.—Variation in specific susceptibility (χ) and saturation isothermal remanence (SIRM) and particle size for a deep water core, distal to the Endrick delta. Wet sieve and pipette analyses depicted.

<32μm fraction are also depicted in Figure 5. Dispersion of these organic sediments is difficult, but the results suggest there is little variation in the down-core particle-size distribution in these fine fractions. The down-core susceptibility fluctuations can be largely explained by variations in the coarser particle (medium/coarse silt) size ranges.

SIRM/χ ratios vary only between 8 and 12 × 10^3 Am^{-1} down core (Figs. 8, 9) and show a similar small change with grain size (Table 1). This suggests that the size of magnetic crystals varies little with sediment particle size and that the coarser particles contain small magnetic minerals (~1–10 μm) as inclusions.

If down-core susceptibility variations are plotted for various particle size fractions (Fig. 6), maxima and minima can be seen in each profile, but the finer particle-size fractions have a general higher level of susceptibility than the coarser material. The only exception to this pattern is the top 5 cm of sediment with particle sizes of 125–250 μm, the reason for which is not conclusively known but it may be due to atmospheric particulate pollution (Doyle et al., 1976). All particle-size fractions contain a proportion of magnetic minerals, but the proportion varies with particle-size (Fig. 7). The contribution of magnetic minerals in any particular particle-size fraction to the total susceptibility thus simply depends on (i) the magnetic mineral concentration and (ii) the proportion of sample falling in the given size range. In Figure 7 we can see that the higher bulk

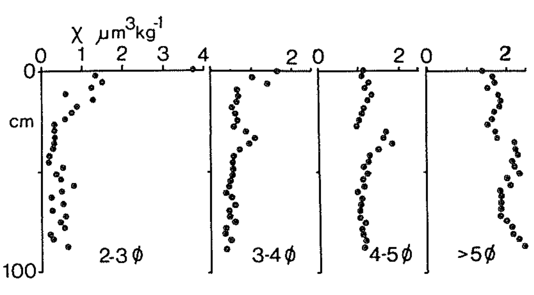

FIG. 6.—Down core variation in specific susceptibility for various particle size fractions for a shallow water, delta-top core LLARM6 (refer Fig. 4).

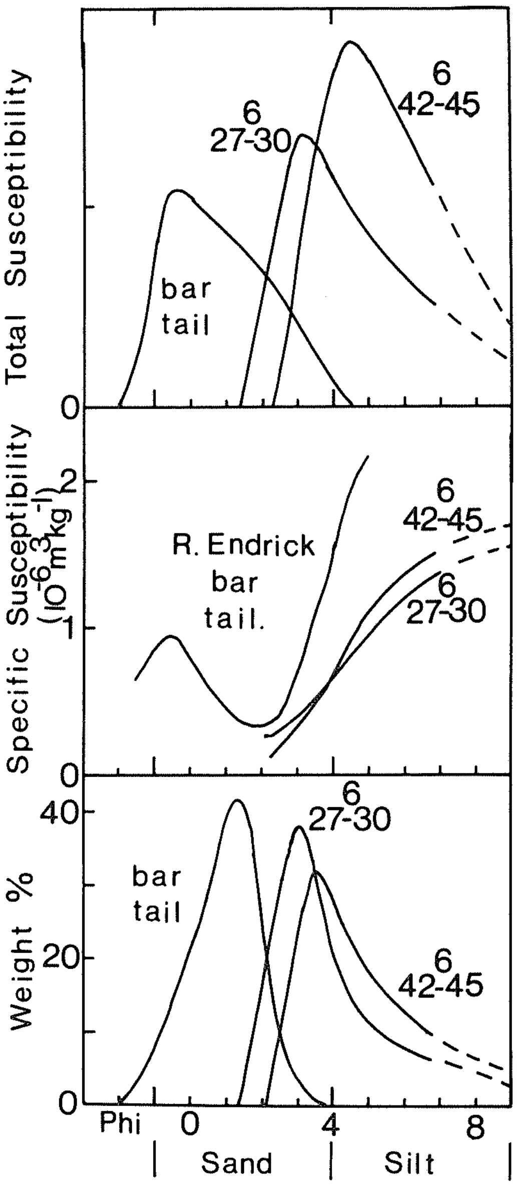

FIG. 7.—Particle size vs dry weight percentage, specific susceptibility and total susceptibility for core LLARM6 depths 270–300 420–450 mm and a River Endrick bar tail deposit. Bulk susceptibility is equivalent to the area beneath a total susceptibility curve.

susceptibility of sample 42–45 compared with 27–30 (Fig. 4) results from the higher coarse silt content. This is due to the change in particle-size distribution between the samples and not a change in mineralogy. Note how the change in coarse silt content is amplified by the concentration (specific susceptibility) curve and is consequently more important than the modal fine sand fractions in influencing the total susceptibility.

By plotting this total susceptibility distribution against particle-size for a number of samples from the River Endrick drainage system (three samples illustrated in Fig. 7) it can be seen that there is a trend for the high specific susceptibilities to occur in the fine-particle sizes. However, there is no instance where the major contributor to the susceptibility corresponds to the finest silt or clay fractions. Instead the bulk of the total susceptibility occurs in sand size fractions in the proximal river deposits and in the medium to coarse silt fraction in the distal core material from the lake.

THE CHEMICAL AND PALYNOLOGICAL RECORDS

The major cations and loss of ignition were analysed for different particle-size fractions of four samples from cores LLARM6 and LLTOM4 (Table 2). The chemical variations are clearly dependent on particle size rather than depth or age. Only MnO varies between the near shore and deep-water sites, presumably due to a difference in redox potential at the two sites. Down-core changes in chemistry can be explained by variations in particle-size distribution rather than a change of source material in the drainage basin. Little work has been previously carried out on the relevance of particle-size to chemistry in lake sediments and down-core variations have been explained in changing source material, e.g., by increased leaching (Mackereth, 1966) or by deeper erosion of illuviated soils (Davis and Norton, 1978). The present work highlights the large chemical variations between particle sizes and illustrates their possible importance even in deep deposits of large lakes.

Phases of forest clearance are recorded in the pollen and spores spectra of the sediment as high non-arboreal pollen assemblages (Dickson et al., 1978). High percentages of *Gramineae, Plantago lanceolata, Pteridium, Calluna, Cyperaceae,* and *Filicales,* reflecting these clearances, only occur where susceptibility values are high. This relationship is very similar to, but not quite as pronounced as, that described for L. Neagh (Thompson

TABLE 2

ϕ		cm	10^{-3}Am^{2}kg^{-1}	10^{-6}m^{3}kg^{-1}	Percentage							
Phi	Core	Depth	SIRM	χ	SiO_2	Al_2O_3	Fe_2O_3	K_2O	TiO_2	MnO	P_2O_5	Ignition Loss
2–3	6	33–36	2.4	0.32	90.	5.0	1.5	1.4	0.4	0.02	0.05	0.0
3–4	6	33–36	4.5	0.96	82.	7.3	3.3	1.7	1.0	0.04	0.12	1.7
3–4	6	51–54	4.7	0.47	80.	8.4	2.3	2.0	0.5	0.04	0.09	2.6
4–5	6	33–36	8.4	1.3	76.	9.4	4.0	1.8	1.4	0.05	0.19	3.3
4–5	6	51–54	8.4	1.1	76.	9.9	3.2	2.0	0.9	0.04	0.15	3.0
2–5	4	80–90	3.6	0.45	70.	11.0	5.5	1.9	0.7	1.48	0.36	5.0
2–5	4	20–30	7.0	0.94	64.	13.1	5.6	2.4	0.9	1.40	0.19	8.2
>5	6	33–36	17	1.5	56.	16.0	8.1	2.8	1.5	0.07	0.32	9.1
>5	6	51–54	20	2.1	56.	15.5	7.6	2.8	1.4	0.07	0.28	10.7
>5	4	20–30	16	1.6	53.	18.3	9.0	3.4	1.3	0.20	0.27	9.7
>5	4	80–90	12	1.1	52.	18.1	10.9	3.3	1.3	0.30	0.32	8.8

et al., 1975). Considering the differences between and within the drainage basins such simple, consistent relationships are unexpected and must result from a basic underlying cause. The clearance phases, of increased erosion and sediment accumulation, surprisingly supplied the finest sediment to the lake. The times of greatest disturbance in the drainage basin, taken to be marked by the specific susceptibility peaks, are dated at 900, 1300 and 1650 A.D., and the present day.

PALAEOMAGNETIC ASPECTS

The Lomond sediments carry an excellent palaeomagnetic record of ancient geomagnetic field changes (Fig. 3; Dickson et al., 1978; Turner and Thompson, 1979). The intensity of natural remanence closely matches the susceptibility of the sediment. The detrital origin of magnetic minerals contributing to the susceptibility suggests the remanence is also detrital in origin. The remanence is most probably post detrital being produced by the smallest particles aligning in the water filled interstices and being 'locked in' to the sediment by compaction or growth of gels (Stober and Thompson, 1977).

Although lake sediments carry a clear signal of ancient field direction changes, attempts to recover ancient field intensity changes have met with limited success. The standard approach is to normalize the palaeomagnetic intensity (NRM) record using a bulk magnetic property, e.g., susceptibility, anhysteretic remanence or isothermal remanence (Johnson et al., 1948; Kent and Opdyke, 1977). Coercivity spectra may be used to test that the magnetic property and natural remanence lie in similar magnetic minerals (Levi and Banerjee, 1976). The Lomond results demonstrate that laboratory remanence (e.g., SIRM) depends on the sediment particle-size distribution and is dominated by the silt-sized particles. NRM, however, is carried by smaller particles and dominated by variations in the finest fractions. The standard normalization procedures thus fail to allow for down-core particle-size variation except when the NRM intensity and normalizing property have identical contributions throughout their particle-size spectra.

CARRIER OF SUSCEPTIBILITY IN THE LAKE CORES

When SIRM against χ is plotted for dried-weight bulk samples from the River Endrick (Fig. 8) there can be seen to be a marked trend of decreasing magnetic concentration in progressively distally located samples. The bulk data from core samples taken on the delta and distal to the delta correspond fairly well with data for samples taken from distal locations within the River Endrick itself. This relationship would suggest a link between sedimentation in the River Endrick and the immediately distal lacustrine area with the River Endrick being the major contributor of detrital sediment to the lake. Since χ is taken as an estimate of the magnetic mineral content of the sample (Fig. 7), there is the implication that the susceptibility of the lake sediment is reflecting the detrital sediment supply.

Although there is a decrease in χ of sediments towards the distal end of the drainage

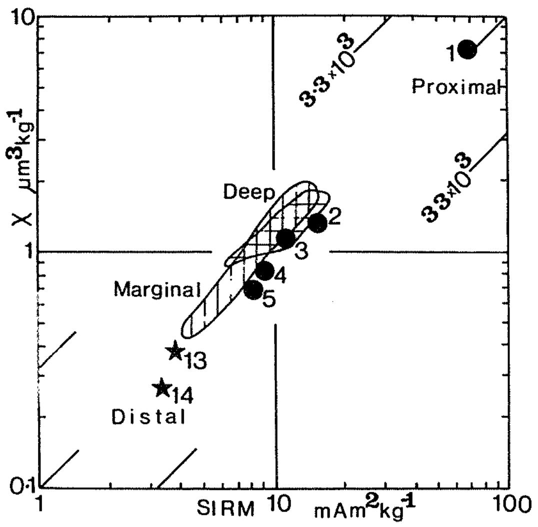

FIG. 8.—A plot of saturation isothermal remanence against specific susceptibility on log/log scale for dried weight bulk samples from the River Endrick and from cores taken both on and beyond the Endrick delta.

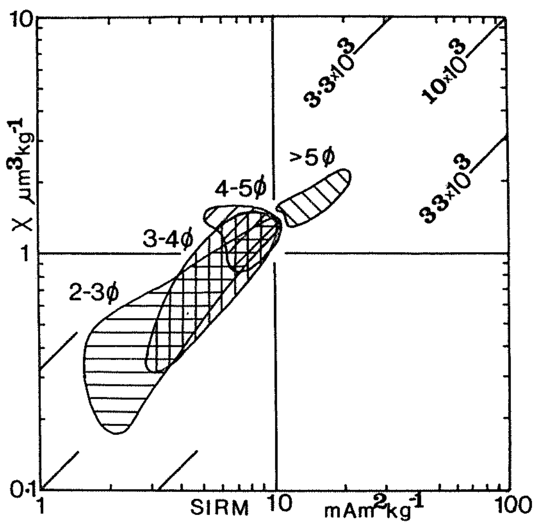

FIG. 9.—A plot of saturation isothermal remanence against specific susceptibility on log/log scale for dried weight samples of various particle size fractions (from Fig. 6) from a 1-m core taken on the Endrick delta.

system, there does not appear to be any major change in the mineralogy of the bulk sediment samples. The constant SIRM/χ ratios (Fig. 8) taken together with the constant values of B_{CR} (20–40 mT) of the lake samples show there are no major mineralogical differences. 'Magnetite' is the dominant magnetic mineral present in each case. Similarly there is no mineralogical change with particle-size for the various samples down a core (Fig. 9). The plot of SIRM against χ (Fig. 9) shows a constant SIRM/χ ratio for the particle size fractions, which also have B_{CR} values of 20–30 mT, indicating that 'magnetite' is again the dominant magnetic mineral in all fractions.

A number of sources of the magnetic minerals have to be considered. 'Magnetite' may be derived from a primary source of bedrock or till. Secondary iron oxides form in top soil (LeBorgne, 1955) and are a potential source. Secondary magnetite may form by burning, or secondary maghaemite may form by natural pedogenic processes. Magnetic minerals derived from any of these sources could have been transported as detritus into the lake. Alternatively, secondary magnetite could have resulted from authigenic growth at the mud/water interface within the lake. Finally, the magnetic mineralogy could even be the result of wind-borne material deposited in the drainage basin.

All of these sources for the magnetic minerals are possible but with different degrees of likelihood. Wind-borne material is unlikely to be a major contributor as the concentration in ombrotrophic peat bogs is low in pre-industrial times (Oldfield et al., 1978). Equally, there is no evidence to support the growth of authigenic magnetic minerals in Loch Lomond. Authigenic minerals are ruled out by the core to core correlations of Figure 2 and the absence of mineralogical changes either between stream and lake sediment (Fig. 8) or down a core (Fig. 9). The derivation of primary magnetic minerals from bedrock, till or top soil is the preferred explanation as the soils of the drainage basin are very immature and their original magnetic content high.

DISCUSSION OF DOWN-CORE SUSCEPTIBILITY VARIATIONS

There is a clear relation between particle-size and susceptibility. Three models are examined to account for the down-core variation of particle-size distributions:

1) Two or more sources.

2) Differential erosion/transportation of one source.
3) Change in depositional environment.

Variation in source material could occur on the scale of enhanced erosion of a particular river or on the scale of change in soil wash/bankside erosion. The latter type of variation resulting from land-use changes would fit many of the observations at Loch Lomond.

In this model the prime source of the magnetic minerals would be the secondary magnetite developed in the soils, probably in the fine-particle sizes. During periods in which the soils of the drainage basin were disturbed, possibly by farming, ploughing or forest clearance, as has been suggested (Thompson et al., 1975), fine particles of top soil would be released for transport in the rivers and increase the rate of inorganic influx to the lake. Consequently, down-core changes in concentration of magnetic minerals reflected in susceptibility variations would be related to changes in the land use of the drainage basin where periodic increases in soil erosion provided a supply of fine sediment high in magnetic mineral content for deposition in the lake. Magnetic analyses of suspended sediments and source materials in an instrumented catchment near Exeter (Oldfield et al., 1979) indicate that secondary ferrimagnetic minerals in topsoil constitute the main magnetic source material in this region. However, there are difficulties in the Lomond basin in that the between-stream variations in susceptibility and IRM tie in with the geology rather than land use of the drainage basin, while, similarly, variations in susceptibility between drainage basins also fit geology rather than land use. Finally, and perhaps most significantly, there is a distinct lack of mature soil profiles within the Loch Lomond drainage basin which could serve as a source for the secondary ferrimagnetic iron oxide.

In the second erosion/transport model the major supply of ferrimagnetic minerals would always be primary 'magnetite' from the bedrock or tills. The ferrimagnetic minerals could and probably would pass through a soil-forming stage. The differential erosion could be produced by land-use changes. Decrease of free cover could lead to increased rain splash action on the topsoil or increased overland flow, both of which could lead to an increase in supply of fine particles. Sorting during transport could help concentrate the heavy minerals. This model would produce the susceptibility and IRM variations observed within a stream (Fig. 8), between streams, and between near shore and deep-water cores within one drainage basin and also the variations between drainage basins where the magnetic properties best agree with geological rather than land-use parameters. In this model down-core changes result from land-use changes leading to erosion of the finer fraction of a single source material.

The depositional model will also explain the particle-size/susceptibility correlation (Fig. 4) and down-core fluctuations. In a fluvially dominated system, coarse material may represent high-energy deposition with the finer-particle deposits either representing lower energy conditions of deposition, the products of winnowing out of finer sediment from coarser deposits on the falling flood stage, or possibly reflecting deposition in overbank areas between channels on the delta top. The coarse and fine horizons in cores, both on and distal to the delta and corresponding to minima and maxima in susceptibility, would be explained in terms of depositional conditions with the vertical repetition of coarse and fine material in the core being the result of shifts in the relative positions of the topographic features on the depositional surface (i.e., channels and overbank areas). Such a model would help to explain the relationship between susceptibility and particle-size, but the similarity of records from various basins of the lake and the correlation of finer deposits with forest clearance periods would remain difficult to explain.

CONCLUSIONS

1) There is a relationship between magnetic susceptibility and particle-size.

2) Magnetic susceptibility can be used to establish a lithostratigraphy for lacustrine sediments directly from the rapidly acquired magnetic data without the need for sub-sampling all cores.

3) Variations in other magnetic properties (e.g., SIRM) are also controlled by particle-

size and so these parameters can also be used to establish a stratigraphy in lake sediment cores.

4) The chemical record even in large deep lakes may be influenced by particle-size variations.

5) Down-core particle-size variations invalidate standard palaeointensity estimates.

6) The major source of ferrimagnetic iron oxides in Loch Lomond is primary 'magnetite'.

7) Down-core susceptibility fluctuations and the correlation of susceptibility maxima with decrease in sediment particle-size and increase in palynological forest clearance indicators can be explained by increased erosion of fine particles from surface materials.

8) The down-core measurements of susceptibility can be used for establishing linkages in the lake-watershed ecosystem.

ACKNOWLEDGMENTS

We thank NERC for financial support, F. Oldfield for coring assistance and discussions on many aspects of the project, and J. G. Fitton for help with chemical analyses.

REFERENCES

DAVIS, R. B., AND NORTON, S. A., 1978, Paleolimnologic studies of human impact on lakes in the United States, with emphasis on recent research in New England: Polish Archives of Hydrobiology, No. XXV 1/2, p. 99–115.

DICKSON, J., STEWART, D., THOMPSON, R., TURNER, G. M., BAXTER, M., DRNDARSKY, N. D., AND ROSE, J., 1978, Flandrian marine and freshwater sediments of Loch Lomond, Scotland: Palynology, palaeomagnetism and radiometric dating: Nature, v. 274, p. 548–553.

DOYLE, L. H., HOPKINS, T. L., AND BETZER, P. R., 1976, Black Magnetic Spherule Fallout in the Eastern Gulf of Mexico: Science, v. 194, p. 1157–1159.

ELLIOT, T., 1977, The variability of modern river deltas: Sci. Prog., v. 64, p. 215–227.

JOHNSON, E. A., MURPHY, T., AND TORRENSON, O. W., 1948, Prehistory of the Earth's magnetic field: Terr. Magn. Atmosph. Elec., v. 53, p. 349–372.

KENT, D. V., AND OPDYKE, N. D., 1977, Paleomagnetic field intensity variation recorded in a Brunhes epoch deep-sea sediment core: Nature, v. 266, p. 156–159.

LEBORGE, E. 1955, Abnormal magnetic susceptibility of the topsoil: Annals. Geophys., v. 11, p. 399–419.

LEVI, S., AND BANNERJEE, S. K., 1976, On the possibility of obtaining relative paleointensities from lake sediments: Earth Planet. Sci. Letters, v. 29, p. 219–226.

MACKERETH, F. J. H., 1958, A portable core sampler for lake deposits. Limnol. Oceanogr., v. 3, p. 181–191.

———, 1966, Some chemical observations on post-glacial lake sediments: Phil. Trans. Royal Soc. London, ser. B, v. 250, p. 165–213.

———, 1969, A short core sampler for subaqueous deposits: Limnol. Oceanogr., v. 14, p. 141–151.

———, 1971, On the variation in direction of the horizontal component of remanent magnetization in lake sediments: Earth Planet. Sci. Letters, v. 12, p. 332–338.

MOLYNEUX, L., 1971, A complete result magnetometer for measuring the remanent magnetization of rocks: Geophys. Jour. Astr. Soc., v. 24, p. 429–434.

———, AND THOMPSON, R., 1973, Rapid measurement of the magnetic susceptibility of long cores of sediment. Geophys. Jour. Astr. Soc., v. 32, p. 479–481.

———, ———, OLDFIELD, F., AND MCCALLAN, M. E., 1972, Rapid measurement of the remanent magnetization of long cores of sediment: Nature, v. 237, p. 42–43.

OLDFIELD, F., 1977, Lakes and their drainage basins: units of sediment based ecological study: Prog. Physical Geography, v. 1, p. 460–504.

———, THOMPSON, R., AND BARBER, K. E., 1978, Changing atmospheric fallout of magnetic particles recorded in recent ombrotropic peat sections: Science, v. 199, p. 679–680.

———, RUMMERY, T. A., THOMPSON, R., AND WALLING, D. E., 1979, Identification of suspended sediment sources by means of magnetic measurements: some preliminary results: Water Resource Research (in press).

STOBER, J. C., AND THOMPSON, R., 1977, Palaeomagnetic secular variation studies of Finnish lake sediment and the carriers of remanence. Earth Planet. Sci. Letters, v. 37, p. 139–149.

THOMPSON, R., 1973, Palaeolimnology and palaeomagnetism: Nature, v. 242, p. 182–184.

———, 1976, Stratigraphic consequences of palaeomagnetic studies of Pleistocene and Recent sediments: Jour. Geol. Soc. London, v. 133, p. 51–59.

———, BATTARBEE, R. W., O'SULLIVAN, P. E., AND OLDFIELD, F., 1975, Magnetic susceptibility of lake sediments: Limnol. and Oceanogr., v. 20, p. 687–698.

TURNER, G. M., AND THOMPSON, R., 1979, Behaviour of the Earth's magnetic field as recorded in the sediment of Loch Lomond: Earth Planet. Sci. Letters, v. 42, p. 412–426.