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AN INVESTIGATION INTO THE SOURCE OF MAGNETIC MINERALS IN SOME FINNISH LAKE SEDIMENTS

J.C. STOBER and R. THOMPSON

Department of Geophysics, University of Edinburgh, Edinburgh, Scotland (U.K.)

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The source of magnetic minerals in the sediments of five Finnish lakes, which carry a palaeomagnetic record of the geomagnetic field, was found to be primary magnetite in the glacial drift of the catchments. The magnetite is concentrated in the central lake sediments. The ratio of haematite to magnetite was found to decrease in the progression drift-stream bedload-lake sediment. A consistent, temporal decrease of magnetic mineral concentration was found in all the lake sediments studied and is related to maturation of the soils and vegetation surrounding the lakes. This distinctive trend contrasts with that seen in Britain and is discussed in terms of man's influence on landscape development.

1. Introduction

The investigations described in this paper formed part of a palaeomagnetic study of the sediment from five Finnish lakes (Vuokonjarvi (63.4°N, 29.1°E); Pielinen (63.2°N, 29.4°E); Kiteenjarvi (62.1°N, 30.2°E); Paajarvi (61.1°N, 21.5°E) and Ormajarvi (61.2°N, 24.9°E). Geomagnetic variation records were obtained from the stable natural remanent magnetization (NRM) of the sediments. The NRM was found to be carried by spinel structured iron oxides [1]. The magnetic studies described here were made to determine the source of the magnetic minerals in the lake sediments.

The bulk of the dry matter of lake sediments may be either allochthonous (derived from the drainage basin) or autochthonous (produced biochemically within the lake). Mackereth [2] from a study of the chemistry of lake sediments in northwestern England, an area of high relief and steep slopes, suggested that the lake sediments were derived principally from soils of the drainage areas, with little addition from the biomass of the lake. In other regions, particularly where lake productivity is higher, meromixis of lake water is more common, and relief lower, autochthonous sediments may be more common. Four possible sources of strongly magnetic particles in lake sediments are (1) detrital primary ferrimagnetic minerals derived from the bedrock and/or drift, (2) detrital secondary (neoformation) ferrimagnetic minerals produced in the soil, (3) atmospheric ferrimagnetic minerals probably derived from outside the drainage basin, and (4) authigenic ferrimagnetic minerals.

The first source has been proposed for catchments dominated by basic igneous rocks such as Lough Neagh [3]. The second source could be of particular importance if topsoil provides a significant proportion of the detritus carried into lakes by streams and by downslope drainage as the magnetic susceptibility of topsoil has been found, in many instances, to be much greater than that of the subsoil or parent material, due to the secondary development of ferrimagnetic minerals [4,5]. Oldfield et al. [6] have studied the source of suspended sediment in Jackmoor Brook, Devon, using magnetic measurements and have found that arable topsoil, in which secondary ferrimagnetic minerals had been developed, was the main source of the sediment. The third source can be discounted except in most unusual circumstances, e.g. tephra and recent, nearby industrial coal burning [7]. It is not considered further. The fourth source was considered by F.J.H. Mackereth (personal communication, 1971) to be possible in lakes of northwestern England. He thought the biochemical conditions at the mud/water interface were suitable for the growth of authigenic magnetite, and that the positive correlation of NRM intensity and organic carbon content also pointed to authigenic magnetite growth. Jones and Bowser [8], however, in reviewing the mineralogy of lake sediments only report occurrences of authigenic ferrimagnetic iron sulphides and not magnetite.

Standard mineralogical investigations of lake sediments are hampered by (1) the fine particle size (mode generally about 5 μm), (2) the organic content (organic carbon generally between 1% and 10%), and (3) the great mixture of minerals originating from a range of sources. For example, particle size analyses are hindered by dispersal problems as are magnetic concentration procedures, while thermomagnetic experiments are severely complicated, particularly in organic rich samples by chemical changes during heating. Kodama et al. [9] have discussed the characterization of iron oxides in soils. The difficulties they outline in X-ray, chemical, infrared absorption and differential thermal methods are highlighted in lake sediments due to the low concentrations of iron oxides. They clearly demonstrated the value of the Mossbauer method in analysing small amounts of haematite of 1% or less, but noted difficulties caused by very fine grain sizes and mixtures.

Much of the iron in lake sediments and soils occurs as poorly crystalline to amorphous coatings, goethite, organic complexes or associated with clay minerals, while the ferrimagnetic mineral content of the samples we investigated ranged from roughly 1 ppm to 0.1%. Also the magnetic grain size, even within individual samples, varied from less than 0.02 μm (superparamagnetic) to over 10 μm (multidomain), and the mineralogy probably spanned the complete magnetic-maghaemite solid solution series with variable amounts of impurities. So precise mineralogical identification of the ferrimagnetic minerals is not routinely practical in such sediments. The high-coercivity magnetic minerals have a similar range of concentrations and magnetic grain sizes as the ferrimagnetic minerals. They probably have a composition close to haematite. Again variable amounts of impurities are likely in these magnetic minerals with a great mixture of sizes and compositions in each individual sample making mineralogical characterization extremely difficult.

Five Finnish lake catchments were studied to investigate the possible sources of magnetic minerals and their changing importance through post-Glacial times until the present day. The results from one catchment, Kiteenjarvi which lies to the south of Joensuu in southeastern Finland (62.1°N, 30.2°E), are first described in detail. Despite the complexity of the mineralogy within individual samples consistent spatial and temporal magnetic trends are found. These trends are also found in the four other catchments under study. Finally a comparison, in terms of regional patterns, is made with other European catchments.

2. Sampling and magnetic measurements

Soil and drift profiles were dug in both forested and agricultural land to depths of up to 70 cm and samples were taken at 5- to 10-cm intervals. Sediment samples were collected from the bedload of streams flowing into the lake and were taken from as near to the centres of the channels as practicable. The sampling sites around Kiteenjarvi are shown in Fig. 1. Bedrock samples were also collected.

In the laboratory, the soil, drift and stream sediment samples were sieved using a 2-mm mesh to remove pebbles and coarse organic debris. If necessary, finer organic material was floated off in water. The samples were then dried. Plastic cylinders with a volume of 10 ml were weighed and samples put into them. After reweighing the cylinders were packed with clean, non-magnetic foam rubber to prevent movement of the particles during measurement.

The magnetic susceptibility, χ, of each sample was measured using a susceptibility bridge and samples were subjected to magnetic fields of up to 10 kOe to find the saturation remanent magnetization, J_{rs} (J_{rs} here is thus defined as the remanence grown in 10 kOe). Back magnetic fields were used to find the coercivity of remanence, H_{cr}, at which the isothermal remanence (IRM) was reduced to zero.

Magnetite saturates at 1 or 2 kOe but fine-grained haematite requires much larger fields for saturation.

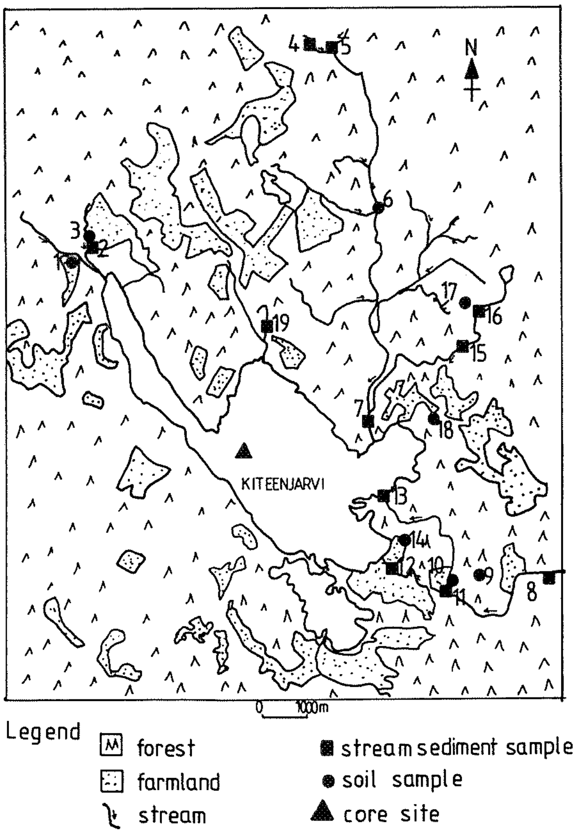

Fig. 1. Sampling sites in and around Kiteenjarvi.

The parameter S, where:

$$S = -\frac{\text{back IRM at 1 kOe after "saturation" at 10 kOe}}{J_{rs}}$$

was therefore calculated to give some idea of the relative proportions of magnetite and haematite present in a sample. The saturation magnetization of haematite is about 0.4 G cm^3 g^{-1} and that of magnetite roughly 90 G cm^3 g^{-1}, a sample has to contain at least ten times as much haematite as magnetite for the haematite to be detected. S is low for a sample with a high haematite to magnetite ratio. If magnetite alone is present, S is unity (Table 1).

The magnetic susceptibility, χ, of natural samples is roughly proportional to their ferrimagnetic mineral content [10,11]. Saturation remanence, J_{rs}, is also dominated by ferrimagnetic mineral content. The magnetic parameter H_{cr} and ratio J_{rs}/χ, however, depend on the types and sizes of magnetic minerals rather than their concentrations. Typical values of these parameters for different minerals are given in Table 1.

3. Magnetic measurements made on lake sediments

In order to compare magnetic properties of catchment samples with the organic lake sediments, nineteen subsamples were taken from a range of depths in

TABLE 1

Summary guide of magnetic properties of natural minerals, and soil/drift, stream bedload and lake sediment in the Kiteenjarvi catchment

Material	Particle fraction	N	χ (G Oe^{-1} cm^2 g^{-1})	J_{rs} (G cm^2 g^{-1})	J_{rs}/χ (Oe)	H_{CR} (Oe)	S
Soil and drift	bulk	45	10×10^{-6}	380×10^{-6}	38	480	0.51
	<32 μm	28	11×10^{-6}	360×10^{-6}	33	460	0.54
Stream bedload	bulk	9	7×10^{-6}	410×10^{-6}	60	380	0.75
	2000–500 μm	7	5×10^{-6}	880×10^{-6}	170	280	0.82
	500–125 μm	8	3×10^{-6}	290×10^{-6}	90	380	0.69
	125– 32 μm	8	6×10^{-6}	470×10^{-6}	70	290	0.78
	<32 μm	9	12×10^{-6}	1200×10^{-6}	100	370	0.74
Lake sediment	bulk	19	30×10^{-6}	3010×10^{-6}	100	410	0.95
magnetite	>20 μm	–	5×10^{-2}	<1	<20	<200	1.00
magnetite	0.1–1 μm	–	5×10^{-2}	>10	~200	~400	~1.00
magnetite	<30 nm	–	0.5	~0	<1	~0	–
haematite	–	–	5×10^{-5}	0.2	>2000	>2000	<0.00
goethite	–	–	5×10^{-5}	~0	~0	~0	–

N = number of samples. χ = apparent initial reversible susceptibility. J_{rs} = isothermal saturation remanence grown in a field of 10,000 Oe. H_{cr} = dc coercivity of J_{rs}. S = negative ratio of isothermal remanence produced in a reverse field of 1000 Oe after saturation in a forward field of 10,000 Oe to J_{rs}. Geometrical means calculated for χ, J_{rs} and H_{cr}; arithmetic mean calculated for S.

one of the Kiteenjarvi sediment cores collected from the site shown in Fig. 1. These samples were allowed to dry in the sample holders after which their magnetic properties were measured and their weights calculated.

Post-extraction chemical changes of the magnetic mineralogy of lake sediments can result from temperature changes and dehydration. During our experiments no significant changes in magnetic properties between whole core, wet subsample or dry subsample measurements were found except for a decrease in NRM intensity during dehydration. This magnetic change resulted from movement of small ferrimagnetic particles towards larger particles due to surface tension attraction rather than chemical alteration.

The H_{cr}, J_{rs}/χ and S values show that ferrimagnetic particles are the dominant magnetic mineral present in the lake sediment samples (Table I). H_{cr} and S values are similar for most of the samples, an exception being the low H_{cr} values, combined with high S values, between 150 and 220 cm depth where the magnetite is probably coarser grained. The generally high S values, all >0.89, show haematite to be of little magnetic importance in the sediments of Kiteenjarvi.

4. Magnetic measurements made on soil, drift and bedrock samples

The maximum depth of soil found in the cultivated fields was about 250 mm. In the forested areas the uppermost layer usually consisted of peaty material. In both the arable and forest profiles, glacial deposits of sand and clay were encountered beneath the top layer. Parts of the soil and drift profiles were often found to be stained orange in colour, suggesting secondary development of iron minerals (e.g. goethite) had occurred within the tills.

Two samples of the poorly exposed mica gneiss surrounding the lake basin were collected. Both have higher H_{cr} values (~540 Oe) than the lake sediment samples. Their S values of 0.65 and 0.55 indicate that haematite is present in the mica gneiss. Bedrock was never reached in any of the soil and drift profiles which were dug.

χ values in the field soil/drift profiles do not increase towards the top but there is some tendency towards higher χ values at the top of the forest profiles. J_{rs} values range from 40 to 2800 μG cm^3 g^{-1}. Changes in χ and J_{rs} down the profiles are probably attributable to primary, stratigraphic changes in the drift composition.

The soil and drift J_{rs} and χ values are summarized in Table 2 and plotted and compared with the lake sediment data in Fig. 2a. Some overlap of soil and drift values with lake sediment values is apparent, but in general the J_{rs} and χ values of the soil and drift samples are lower than those of the lake sediments (Table 1). The low J_{rs}/χ ratios indicate an appreciable superparamagnetic component.

As lake sediments are fine-grained, being predominantly clay and fine silt, the soil and drift samples were sieved so that the <32-μm particle size

TABLE 2

Depth-age relations used in fitting cubic spline functions to convert sediment depth to conventional ^{14}C ages for Fig. 7a. Ages based on pollen assemblage zones particularly the Spruce invasion ~5000 years B.P. and the Pine/Birch transition which varies between 8200 and 9200 years B.P. in eastern Finland [13] and late-glacial lithologies

Paajarvi		Ormajarvi		Vuokonjarvi		Pielinen		Kiteenjarvi	
depth (m)	age (yr)	depth (m)	age (yr)	depth (m)	age (yr)	depth (m)	age (yr)	depth (m)	age (yr)
0.50	1400	1.10	3000	0.50	1000	2.00	6000	1.00	2500
1.20	2500	1.90	4500	1.00	2800	2.60	8000	1.20	3000
2.40	4400	2.80	5500	2.00	5600	3.05	9000	1.50	3200
2.80	5100	3.35	6500	3.00	7000	4.80	9500	1.70	4000
4.00	6000	3.90	8000	4.00	8400			2.10	5100
4.80	8600	4.30	8800	4.50	9200			4.00	8000
5.10	9000	4.60	9000	6.00	9500			5.20	8600
5.50	9200							6.00	8900

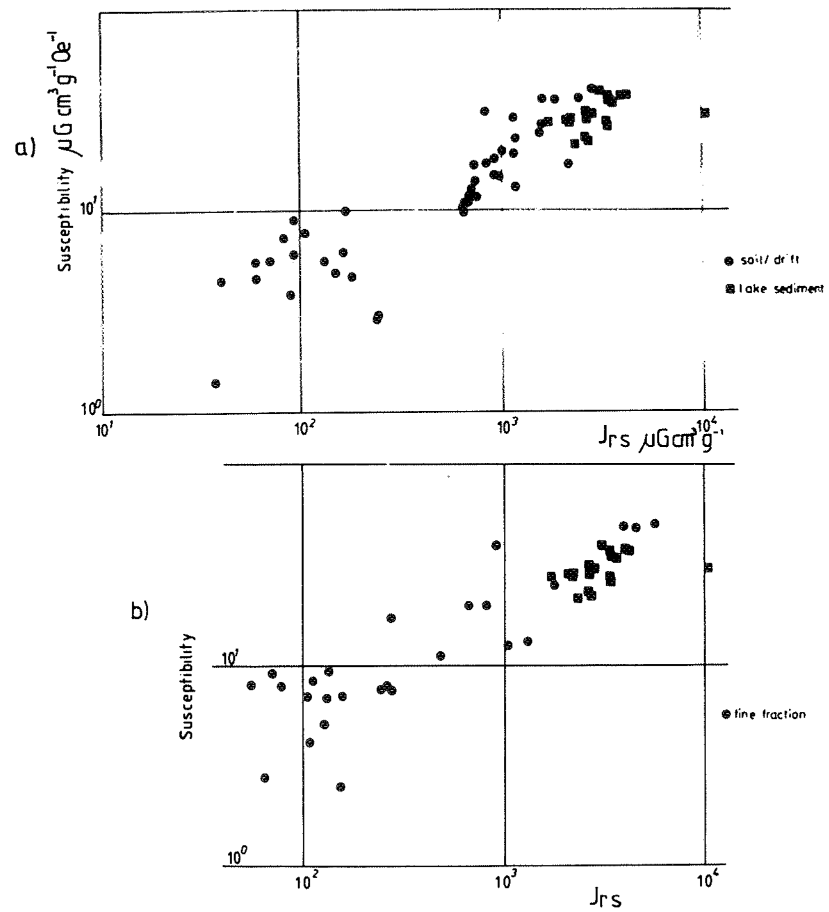

Fig. 2. Comparison of J_{rs} and susceptibility data from (a) bulk soil and drift, and (b) fraction of grain size <32 μm with lake sediment sample data.

fraction could be compared with the lake sediment data. A wet sieve tower was used to collect the fraction of grain size <32 μm for five of the seven profiles. Magnetic measurements were then made on the dried <32-μm fractions. J_{rs} and χ results for these fine fractions and the lake sediments are plotted in Fig. 2b. The overall distribution of data is very similar to that of the bulk samples.

5. Magnetic measurements made on stream bedload sediments

Samples of stream bedload were collected in order to investigate the transport of magnetic minerals from the drainage basin to the lake. It was supposed that the finer fraction would resemble the suspended sediment which had been transported further downstream to the lake.

Magnetic measurements were first made on the bulk samples. These results are summarized in Table 1. Values of both J_{rs} and χ were lower than the lake sediment results but values of S were closer to those of the lake sediments than were the soil and drift sample values. This implied a decreased magnetic importance of haematite in the stream sediments compared with the soil and drift samples. The J_{rs} and χ values are plotted in Fig. 3a where they are compared with the lake sediment data. It can be seen that the best fit to the lake sediment data was pro-

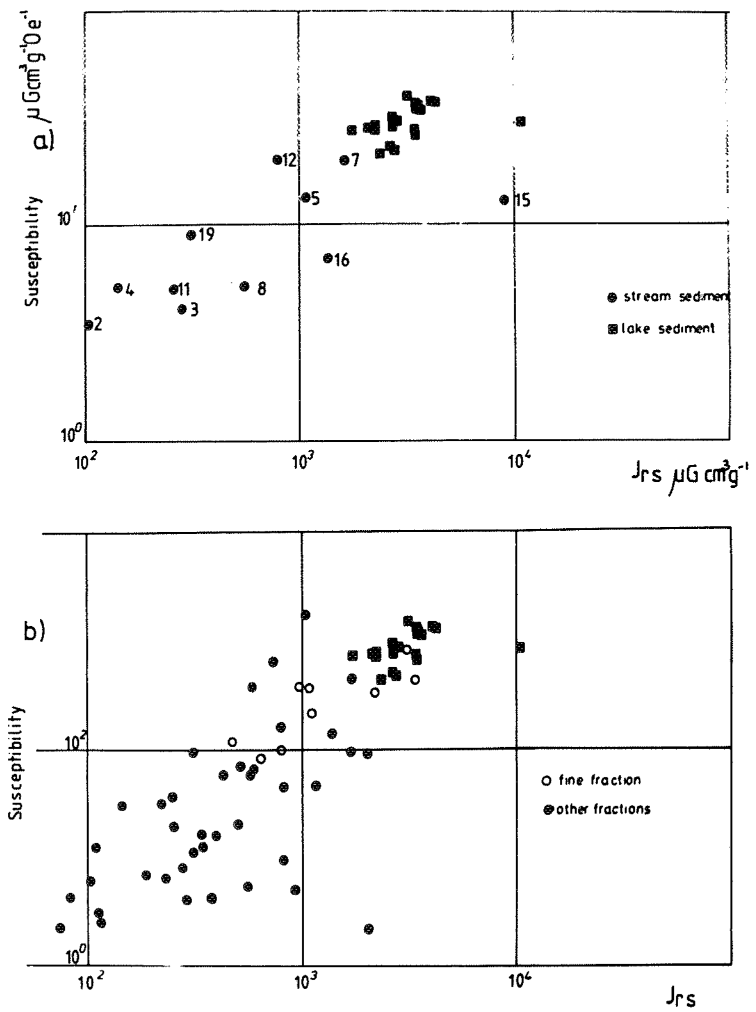

Fig. 3. Comparison of J_{rs} and susceptibility data from (a) bulk stream sediment, and (b) sieved fractions with lake sediment sample data.

vided by sample 7 from near the main river mouth. The coercivity of this bulk sample was, however, much lower than the lake sediment values.

Sample 16, taken from a stream draining a small lake, had a coercivity of only 165 Oe and this along with the other data indicated a high proportion of coarse-grained magnetite in the magnetic mineralogy. Little magnetic evidence of haematite was found in sediments from streams draining small lakes in any of the lake catchments studied.

Nine stream bedload samples were sieved for magnetic measurements and the results are summarized in Table 1. Magnetic measurements on the individual fractions from any one sample did not show well-defined trends with particle size. However, in general, the concentration of ferrimagnetic minerals in the <32-μm fraction, as reflected in the χ and J_{rs} data, was closest to the concentration in the lake sediments. J_{rs}/χ values for seven out of the nine <32-μm fractions were greater than the bulk sample values. Five out of the nine <32-μm fractions had S values of greater than 0.75 and only one had a value of less than 0.6. These differences show how the concentration of magnetic minerals and the haematite/mag-

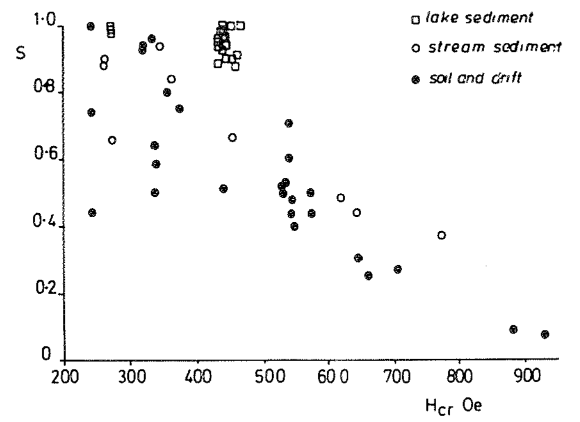

Fig. 4. H_{cr} and S data for Kiteenjarvi lake sediment and catchment samples. Stream sediment and soil/drift samples of grain size <32 μm.

netite ratio change during erosion processes.

In Fig. 4, H_{cr} has been plotted against S for the lake sediment samples and for the <32-μm fractions of the stream bedloads sediments and soil and drift samples. A negative correlation between these two parameters is to be expected because a greater proportion of haematite in the sample will decrease S but increase H_{cr}. However, as can be seen from the diagram, the nature of the negative relationship varies between the lake sediment, stream sediment and soil/drift groups.

6. Discussion

The magnetic results described above can be explained by the soil and drift of the catchment area forming the major source of ferrimagnetic minerals in the lake sediments. Some growth of ferrimagnetic minerals may be occurring in the topsoil but it is unlikely that these form the bulk of the magnetic input to the lake. Bedrock is thought to contribute little directly to the lake sediment, but to have provided the primary source of magnetic minerals during formation of the drift.

The concentration of ferrimagnetic minerals increases by an order of magnitude through the progression soil/drift—stream bedload—deep lake sediment. Hydrological gravity sorting during transport would lead to such a concentration of the dense magnetic minerals. The difference in ferrimagnetic mineral concentration in the lake sediments and in the <32-μm stream bedload probably arises from the bulk of the deep water sediments being finer grained, having been derived during times of flood.

The magnetic parameters H_{cr}, S and J_{rs}/χ also increase during transport of sediment from the catchment to the lake. These parameters indicate that a change in average composition, size or shape of the magnetic minerals has occurred. The increase in S demonstrates that the ratio of ferrimagnetic minerals (such as magnetite) to high coercivity minerals (such as haematite) increases with transportation. An increase in H_{cr} and J_{rs}/χ would also be produced by such a change in average composition. However, a change in the average size (or an elongation of shape) of the ferrimagnetic minerals must also be occurring. This is shown by the different H_{cr}-S relationships in Fig. 4. In the <32-μm soil/drift samples H_{cr} is generally less than in the <32-μm stream bedload samples for corresponding S values. Similarly H_{cr} of the <32-μm stream bedload samples is generally less than the lake sediments for corresponding S values.

During erosion, transport, and deposition, the ferrimagnetic minerals (probably mainly magnetite) are concentrated by a factor of about 5 or 10 whereas the high coercivity minerals (mainly haematite) stay at roughly the same concentration. The difference is not easy to explain. One possibility is if the haematite grains were firmly attached to particles of other composition and lighter density, e.g. clay minerals during authigenic formation in the soil, the gravity sorting would concentrate the magnetite and haematite in different depositional environments. Another possibility is that haematite might be breaking down during transport and sedimentation with the finest grains being reduced by the permanently oxygen-free water layer immediately above the Kiteenjarvi sediments. However, haematite is unlikely to form in soils at such high latitudes and haematite can be stable even in reducing sediments. It would be interesting to investigate a series of sediment cores from the river mouth to the deep-water sediments to gain more information about these differences in mineral concentrations with depositional environment and grain size.

7. Comparison with other lake catchments

The four other Finnish lakes studied in detail differed greatly: lake depth ranged from 7 to 70 m; lake areas varied from 4 to 1000 km^2; bedrock was dominated by mica-gneiss, granite or granodiorite. Surprisingly the main trends observed in the Kiteenjarvi study were also found in all the other catchments as shown schematically in Figs. 5 and 6. In all cases there was a general shift towards higher ferrimagnetic mineral concentration and higher J_{rs}/χ values as the material was transported from the soil/drift to the lake. Also the Kiteenjarvi trends in H_{cr}-S were found for the drift/soil—stream—lake groupings. Our interpretation is that in each basin magnetite became concentrated with transport whereas the haematite concentration remained fairly constant. Sedimentological erosion or transportation processes offer a simpler explanation for these constant regional patterns than limnological processes or geological source material distributions which would be more affected by local factors.

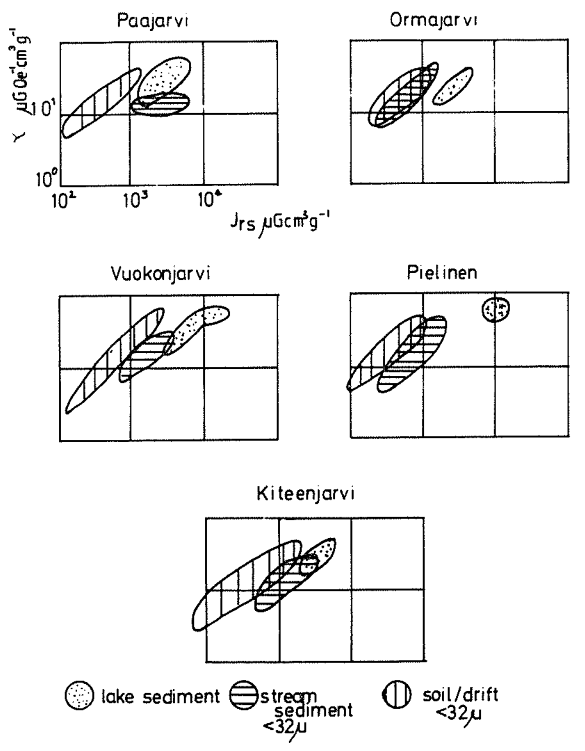

Fig. 5. Diagrammatic comparisons of magnetic measurements made on samples of different types from the catchment areas studied.

8. Temporal variations

A further aspect of the magnetic mineral content of lake sediments is its variation through time. The concentration of ferrimagnetic minerals in the Finnish lake sediments was found to follow a consistent pattern through the last 9500 years. This is most clearly seen in the down-core χ variations (Fig. 7). The χ variations have been scaled to late Glacial clay values in order to facilitate between-lake comparison. Also the susceptibility measurements have been interpolated to equal time intervals in each core by using cubic spline fitting [12] to the age-depth relations of Table 2. The time scales are well defined for Paajarvi, Vuokonjarvi and Kiteenjarvi (Fig. 7) and the British records of Fig. 8. The central sections of Ormajarvi, Pielinen and Hjorstjon have less dating control. Although the down core measurements of Figs. 7 and 8 are based on wet volume rather than dry mass of sediment, the patterns are a reliable estimate of ferrimagnetic mineral concentration as the water content only changes appreciably in the uppermost sediments, which have been excluded from the diagrams. Thus the results cover a period from about 9500 to 250 years B.P.

It is suggested that, while local variations in land use produce the individual features of these records, an underlying regional pattern can be discerned. All the Finnish records show a gradual fall in ferrimagnetic concentration from 9000 to about 4000 years B.P. This is followed by steadier concentrations and a small rise in more recent times. This pattern can be contrasted with those from other northern European lakes (Fig. 8). The southern Swedish record from Hjorstjon (56°N, 14°E) is very similar to the Finnish records. The British records, however, show much more within-core variation and more pronounced increasing concentration trends over the last 5000 years.

The variations in ferrimagnetic concentration of the British records are probably not due to a single physical cause. In Loch Lomond, the variations are closely associated with changes in grain size and are

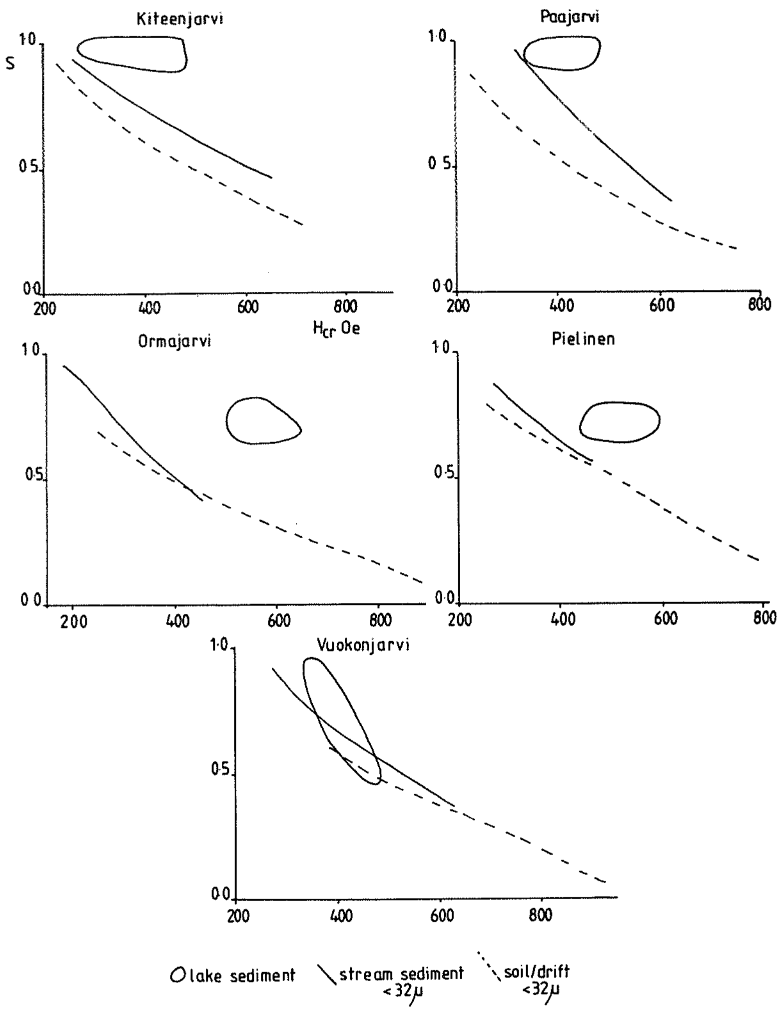

Fig. 6. Summary diagram of trends in the H_{cr} and S data for catchment samples from five Finnish lakes.

taken to reflect erosion of different topsoil fractions. In Lough Catherine the changes in concentration are connected with changes in magnetic grain composition and size and are possibly related to variable erosion of topsoil compared with subsoil or channel banks material. In both Loch Lomond and Lough Neagh the peaks of ferrimagnetic concentration clearly correlate with pollen and spore indicators of increased forest clearance [14].

The difference in magnetic concentration in both the Scandinavian and British records would be further exaggerated if viewed in terms of influx. This is because χ peaks occur at times of high rates of deposition both in the British records where they are associated with forest clearance episodes and in Finland where higher χ values also occur during periods of higher deposition rate.

The consistent pattern of χ variation in Finland and southern Sweden might be expected as a result of processes associated with interglacial maturation of soils and vegetation in the absence of Man, as described by Mackereth [2]. Greater disturbance of the landscape in Britain and northwestern Europe by Man, particularly after the Elm decline would similarly account for the more variable magnetic record. A gradual depletion of sources of fine-grained ferri-

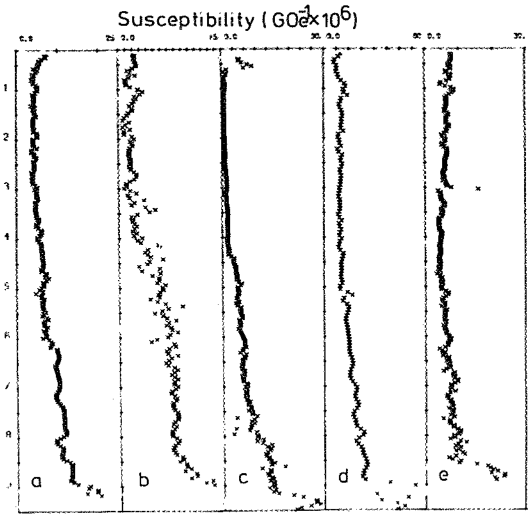

Fig. 7. Susceptibility logs for five Finnish lake sediment cores: (a) Paajarvi; (b) Ormajarvi; (c) Vuokonjarvi; (d) Pielinen; (e) Kiteenjarvi.

magnetic minerals with maturation of the drainage basin coupled with a declining allochthonous contribution to the lake sediments, followed by very recent land use changes (e.g. forest clearance, settlement) uncovering new sources, would account for the general χ trends in Scandinavia of decreasing χ followed by a slight rise in most recent times (Fig. 7a).

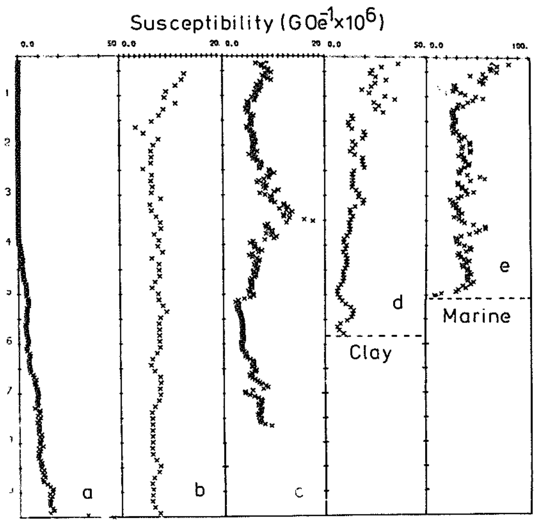

Fig. 8. Susceptibility logs for Swedish and British lake sediment cores: (a) Hjortsjon; (b) Windermere; (c) Lough Catherine; (d) Lough Neagh; (e) Loch Lomond.

This proposed underlying regional difference is also supported by the variation in rate of deposition in the two regions based on a palaeomagnetic chronology [1] and major pollen assemblage zones. For example, the mean rate of deposition of the five Finnish lakes decreases from about 0.8 to 0.4 mm yr^{-1} between 8000 and 2000 years B.P., whereas in Britain the rate of deposition increases from about 0.2 to 0.6 mm yr^{-1} during the same time interval.

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References

1 J.C. Stober, Ph.D. Thesis, University of Edinburgh (1978).
2 F.J.H. Mackereth, Some chemical observations on post-glacial lake sediments. Philos. Trans. R. Soc. London, Ser. B, 250 (1966) 165–213.
3 R. Thompson, R.W. Battarbee, P.E. O'Sullivan and F. Oldfield, Magnetic susceptibility of lake sediments, Limnol. Oceanogr. 20 (1975) 687–698.
4 E. LeBorgne, Abnormal magnetic susceptibility of the top soil, Ann. Geophys. 11 (1955) 399–419.
5 C.E. Mullins, Magnetic susceptibility of the soil and its significance in soil science: a review, J. Soil Sci. 28 (1977) 223–246.
6 F. Oldfield, T.A. Rummery, R. Thompson and D.E. Walling, Identification of suspended sediment sources by means of magnetic measurements: some preliminary results, Water Resour. Res. (in press).
7 L.J. Doyle, T.L. Hopkins and P.R. Betzer, Black magnetic spherule fallout in the eastern Gulf of Mexico, Science 194 (1976) 1157–1159.
8 B.F. Jones and C.J. Bowser, The mineralogy and related chemistry of lake sediments, in: Lakes: Chemistry, Geology, Physics, A. Lerman, ed. (Springer-Verlag, New York, N.Y., 1978).

9 H. Kodama, J.A. McKeague, R.P. Tremblay, J.R. Gosselin and M.G. Townsend, Characterization of iron oxide compounds in soils by Mossbauer and other methods, Can. J. Earth. Sci. 14 (1977) 1–15.
10 H.M. Mooney and R. Bleifuss, Magnetic susceptibility measurements in Minnesota, II. Analysis of field results, Geophysics 17 (1953) 531–543.
11 F.D. Stacey and S.K. Banerjee, The Physical Principles of Rock Magnetism (Elsevier, Amsterdam, 1974).
12 T.N.E. Greville, Introduction to spline functions, in: Theory and Applications of Spline Functions, T.N.E. Greville, ed. (Academic Press, New York, N.Y., 1969) 1–36.
13 H. Hyvarinen, The deglaciation history of eastern Fennoscandia – recent data from Finland, Boreas 2 (1973) 85–102.
14 R. Thompson and D.J. Morton, Magnetic susceptibility and grain size distribution in recent sediments of the Loch Lomond drainage basin, Scotland, J. Sediment Petrol. (in press).
15 J.C. Stober and R. Thompson, Palaeomagnetic secular variation studies of Finnish lake sediment and the carriers of remanence, Earth Planet. Sci. Lett. 37 (1977) 139–149.